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Technical report

Submersible Aircraft Concept Design Study

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14. ABSTRACT

The submersible aircraft study combines the speed and range of an airborne platform with the stealth of an underwater vehicle by developing a vessel that can both fly and submerge. The study explores the feasibility of a design capable of insertion and extraction of Special Forces at greater ranges, higher speeds, and in locations not previously accessible without direct support from additional military assets. The concept design goals are to find a solution space for the feasibility of a vessel capable of multi-modal operations (airborne, surface, and submerged) that can also easily transition between these modes of operation. Within this study a variety of technologies including developing technologies are considered. Materials and structures that provide the desirable characteristics for both a submerged and airborne platform are exploited in order to overcome the major challenges that the design of a submersible aircraft poses.

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Executive Summary

This report outlines a study into the feasibility of a vehicle which aims to combine the speed and range of an airborne platform with the stealth of an underwater vehicle, while capable of managing the transition between these two states. The main aim of the study was to identify the solution space for such a concept employing current technologies.

The concept of such a vehicle has been investigated by the United States Navy (USN) on several occasions since World War II, driven by the perceived tactical advantages that such a platform could offer. The concept is currently of interest to the Defense Advanced Research Project Agency (DARPA) with the aim of inserting Special Forces (SF) covertly at a higher speed and more independently than is currently achievable. DARPA issued a Broad Area Announcement (BAA) in 2008 for such a vehicle and are currently studying proposed designs.

A similar Concept of Operations (CONOP) to that detailed within the DARPA BAA was used for this study, namely:

- Deployment from a naval/auxiliary platform;
- take-off from the water surface and transit 400 miles airborne, then land on the water surface;
- submerge and transit 12 nm underwater before deploying Special Forces;
- loiter for up to 72 hours fully submerged;
- retrieve Special Forces whilst submerged before transiting submerged to 12nm off the coast, take-off and return 400 miles to the mother ship.

The challenges associated with this concept are significant, not least because aircraft and submarines have divergent design requirements. Design drivers for this study focused on four main areas; propulsion, structures, landing / take-off, and vehicle sub-systems.

After initial investigation of the solution space through weight and volume estimations, and wing sizing and design, a flying-wing/blended-body design was adopted as offering the best compromise between airborne and submerged requirements.

Two variations of a submersible aircraft were developed each offering a different arrangement based on the same overall design concept. The key features of this design concept are:

- Division of manned compartments into a two man crew compartment which is a fully watertight pressure hull and one or two compartments for six Special Forces personnel, which is designed to be free flooding when submerged.
- Fuel tanks and ballast tanks incorporated into the wing with the fuel tanks employing a membrane fuel/sea water compensation system.
- All remaining volume within the wing is floodable.
- Twin turbofans positioned to provide uninterrupted airflow and to avoid spray whilst providing power for surface operations.
- An innovative inflatable float system employed for landing and take-off operations.
- Turbofan sealing using torpedo door style hatches to protect them from the harmful effects of sea water.
- Propulsion for underwater operations from a battery powered drop down azimuthing pod providing a speed of 6 knots.
- A sacrificial tethered anchoring system to anchor the vehicle to the sea bed.
- A high pressure air system, designed to blow ballast tanks and floodable areas.

Principal characteristics of the variants are seen in Table 1:

Submersible Aircraft Properties		
Particular	**Variant 1**	**Variant 2**
Wing Span (feet)	92	109
Length (feet)	36	34
Weight (lbs)	37,000	39,000
Payload (lbs)	750	750
Cruise Speed (mph)	200	200
Submerged Speed (knts)	6	6

Table 1: Principal characteristics

Areas of further work are identified within the report, necessary to further validate the assumptions made in this concept study.

Preliminary proof of concept tests have been conducted using a radio controlled model.

The report suggests that a working design is feasible within the current state of the art. It is suggested that any future design expected to meet the requirements of both in air and submerged flight must adopt the approach of a submersible aircraft over that of a flying submarine.

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Nomenclature

A	=	Aspect ratio
B	=	Fuselage width
b	=	Wingspan
C_d	=	Coefficient of drag
C_{D0}	=	Zero lift drag
C_f	=	Thrust coefficient
c.g.	=	Center of gravity
C_L	=	Coefficient of lift
C_M	=	Coefficient of moment
C_{M0}	=	Airfoil moment coefficient of wing about the quarter chord
C_{11}	=	Elasticity tensor
F_w	=	Wrinkle stress
H	=	Fuselage height
I_p	=	Structural pressure index
L	=	Fuselage length, Length
MAC	=	Mean aerodynamic chord
n_{limit}	=	Load factor limit
n_{ult}	=	Ultimate wing loading factor
p	=	Storage pressure
P	=	Maximum pressure differential
P_i	=	Internal pressure
r	=	Vessel internal radius, Radius
Re	=	Reynolds number
St	=	Static margin (stability factor)

S	=	Wing area, fuselage surface area
t	=	Skin thickness, Material thickness, mean chord
t_{root}	=	Root chord thickness
W	=	Fuselage weight
W_{to}	=	Maximum take-off weight
W_{wg}	=	Wing weight
W_{zf}	=	Zero fuel weight
a	=	Angle of attack
a_{total}	=	Total wing twist
a_{geo}	=	Geometric wing twist (washout)
a_L	=	Zero lift angle
σ_θ	=	Cylinder hoop Stress
σ_{long}	=	Cylinder longitudinal stress
E	=	Young’s modulus
υ	=	Poisson ratio
l	=	Aspect ratio
U	=	Angle of sweep at the quarter chord line
Γ	=	Taper ratio
$\Lambda_{c/2}$	=	Wing sweep at the half chord

1. Introduction & background

The concept of a submersible aircraft is not a new one. Military interest in a craft capable of both underwater and in air operation has existed since the early stages of World War Two when a flying variation of a midget submarine was first explored.

In the 1950's, a renewed effort was made to produce a design with the mission profile aimed at prosecuting threats in the Baltic and other 'enclosed' waterways. This culminated in an accepted proposal from *Convair* for a turbojet powered two man design which achieved neutral buoyancy through fuel compensation and flooding the air voids within the engine nacelles with fuel[1]. This concept was widely recognized as feasible but was cancelled by Congress two years after the contract was awarded. In 1964, an American independent defense contractor built and operated a home built prototype of a submersible aircraft. However, only 'short hop flights' were achieved and the United States Navy (USN) showed little interest. In recent years interest has returned to the concept, with the envisaged target mission being covert coastal insertion of a Special Forces team.

The Defense Advanced Research Project Agency (DARPA) has issued a Broad Agency Announcement (BAA) that aims to gather proposals for the submersible aircraft concept. DARPA is interested in this concept due to the significant tactical advantage that such a platform could provide. A submersible aircraft would be capable of fulfilling future coastal insertion missions, providing a game changing Department of Defense (DOD) capability for clandestinely inserting small teams, at coastal locations. A successful design would combine the key capabilities of three different platforms: 1) the speed and range of an aircraft; 2) the loitering capabilities of a boat; and 3) the stealth of a submarine. By combining the beneficial characteristics and the operating modes of each platform, DARPA hopes to develop a craft that will significantly enhance the United States' tactical advantage in costal insertion missions. The DARPA BAA goal is to build a vehicle that could fly 1,000 nautical miles, travel on or close to the surface for 100 nautical miles, move submerged for 12 miles and deliver troops. The craft would then

loiter for up to 72 hours in rough seas before extracting the troops and returning to a safe distance off the coast for refueling. Most proposals discussed to date outline a design which would use a snorkel to supply air to a propulsive plant when submerged and that loiters on the surface a safe distance from the coastline. To date no contracts have been awarded.

2. Concept of Operation (CONOP)

For the purpose of this study, a similar CONOP to that detailed in the DARPA BAA has been chosen, namely:

- Deployment from a warship or naval auxiliary at a defined distance offshore;
- Take-off from the water surface;
- Fly to 12 nm offshore;
- Land on water;
- Fully submerge vehicle and transit 12 nm;
- Deploy Special Forces and equipment whilst submerged;
- Loiter for 3 days fully submerged;
- Retrieve Special Forces whilst submerged;
- Transit 12 nm to safe surfacing zone;
- Take-off from water surface and return 400 miles to the mother ship.

Key differences between the chosen concept of operation and that given by DARPA are the requirement for full submergence during the loitering and transit stages and the requirement to carry sufficient fuel for the whole mission without re-fuelling.

The main purpose of this study is to determine the feasibility of a vehicle capable of operating in both an air and water medium and to identify a solution space for such a design. Because of this the study, although influenced by DARPA’s requirements, has not be constrained by them. In future design iterations the DARPA specific requirements may be analyzed with the solution space identified as a specific case.

3. Key requirements

Initial design requirements are taken from the CONOP with the added requirement that the operating crew must remain onboard the vehicle for the duration of the mission.

Operational requirements are presented in Table 2, developed with the intention of being representative of a realistic mission profile without being so restrictive as to drive the design disproportionably towards focusing on one mode of operation over another.

Operational Requirements[1]		
Crew	2	men
Special Forces	6	men
Flight Range	800	miles
Surface	4	hours
Submerged Transit	12	nm
Loiter	72	hours
Cruise Speed	200	mph
Take-off Speed	100	knots
Submerged Speed	6	knots
Operating Depth	30 [98.4]	meters [feet]

Table 2: Operational requirements

The requirements are conservative based on the main aim of the project to define a solution space. Future studies should asses the consequences of altering these initial requirements on the overall system.

[1] The convention for using statute miles for air ranges and nautical miles for surface and submerged ranges is used within this report.

4. Overview of principal design challenges

The study aims to incorporate three modes of operation; airborne; sea-surface transit; and submerged in water. Significant design challenges exist in producing a vehicle capable of operating in these three environments:

4.1 Density

Aircraft are low density vehicles; weight is a major design driver in order to reduce structural wing loading, landing and take-off speeds, and power requirements. Conversely a submersible is by its definition, a high density design. In order to submerge, its density must be equal the density of the fluid in which it is submerging. If an attempt was made to make a submarine fly, wing loading and take-off powers would be impractical. Similarly if a conventional aircraft were to be submerged it would require large weights to overcome the natural buoyancy of its compartments.

4.2 Pressure

As a vessel is immersed, the pressure it experiences on its outer surface increases dramatically (1 atmosphere per 10m [32.8 feet] of depth). This results in large crushing loads acting on the pressure hull. This is normally countered with substantial plating and structural framework. As a comparison, the pressure differential acting on an aircraft cabin at 40,000 feet [12,192m] is the same as that found at approximately 6 meters [19.7 feet] depth of water. The structure required to resist the crushing loads found at a normal submarine operating depth are significantly larger than those normally found in aircraft and, as such, considerably more heavy.

4.3 Propulsion

Almost all conventional aircraft propulsive units rely on air to oxidise fuel and produce energy. In order to employ an air breathing solution underwater, any design must either carry sufficient air on board to fuel the engine (with the buoyancy issues this brings) or draw air from the surface. This drives the design towards different propulsion solutions for different operating modes.

5. General concept

With candidate technologies identified and an indicative set of requirements determined, it is necessary to outline a general design concept in order to develop the design further. After reviewing a large number of concepts the chosen design approach is outlined below.

5.1 Overall vehicle density

The challenge of meeting the low density requirements of flight and the high density requirements of submersion within a single design is not trivial. Three separate approaches were identified:

1. creating a dense aircraft capable of submerging at the expense of in-air efficiency;
2. creating a low density submersible requiring dynamic lift to stay submerged at the expense of underwater efficiency and loiter capability;
3. creating a design with a highly variable density range at the expense of layout flexibility.

Preliminary calculations showed that the size of a high density solution would be restrictive in terms of deployment from a naval vessel. A low density solution would require some additional submergence force. Whilst dynamic lift underwater could be easily achieved by the already present lifting surfaces, the resulting high induced drag and the complexity of loitering in a submerged state would drive power requirements due to the higher propulsive demands. For these reasons the concept outlined in this report is of a vehicle with large floodable spaces and minimized volume in all systems to reduce buoyancy.

This approach is achieved through the flooding of all non-essential spaces during submersion. The largest buoyant volume in the design is inevitably the Special Forces compartment. The decision was taken to flood this space during underwater transit. Whilst this reduces the comfort level of the Special Forces personnel who will need to breathe through the use of a BIBS (built in breathing system), this is outweighed by the

advantages of dramatically increasing the vehicle density. Current Swimmer Delivery Vehicles (SDVs) employed by the Special Forces involve full immersion of personnel for long periods of time, so the precedent is set for this manner of insertion. The employment of systems such as heaters to raise water temperature is envisaged to improve habitability within the space.

Further to this, the excess buoyancy arising as a result of the volume left by expended fuel is to be compensated by seawater, separated by a flexible membrane from the fuel.

Ballast tanks are also included, located within the non-floodable sections of the wing, allowing depth control without the need to alter the water content of the Special Forces compartment.

5.2 Overall approach to propulsive systems

Whilst a common system allowing propulsion in both mediums (water and air) would be optimal in terms of system weight and volume, it is believed that the technology at present does not offer a viable solution. For this reason separate propulsive systems are selected for the in-air and in-water sections of the mission profile.

With this decision comes the requirement to seal the air breathing flight propulsion module whilst underwater. A watertight hatch similar in implementation to a torpedo tube door is envisaged with the possibility of using the cooling of the engine to induce a low pressure inside the sealed unit, helping with the sealing process.

5.3 Approach to vehicle take-off & landing

The transition from air to water surface and vice versa is hazardous and a fundamental part of the concept design. A number of challenges surrounding take-off and landing exist, as described in the previous section. Any system must give sufficient wing tip clearance from the water surface as well as being sufficiently stable both longitudinally and transversely. It desirable that candidate systems be capable of being stowed and deployed rather than fixed to avoid the resulting parasitic drag of a fixed system whilst in air and submerged. Considered solutions are seen in Table 3, with a discussion of candidate technologies in the following sub-sections.

System Family	System
Aerostatic	Air Cushion
Hydrostatic	Single Planing Hull
	Twin Hulls (Floats)
Hydrodynamic	Surface Piercing Hydrofoil
	Fully Submerged Hydrofoil
	Skis

Table 3: Landing/take-off candidate systems

5.3.1 Air cushion

An air cushion system is an ideal solution in flat sea conditions where there is no wave interference, providing a low drag solution which would minimise propulsive requirements when taking off. At this stage, there is no requirement for the vehicle to take-off in significant sea states. However, it should be capable of landing in more elevated wave conditions. An air cushion solution in waves may cause issues from a seakeeping perspective due to factors such as loss of skirt integrity as it encounters waves. Of equal concern are the powering requirement, and the associated system weights and volumes involved in what is, essentially, a complex system.

5.3.2 Hydrofoils

Hydrofoils offer good seakeeping capabilities as well as low drag characteristics, particularly at higher speeds where frictional drag dominates conventional planing designs. This would make them ideal for reducing the high power requirements at take-off which frequently drive seaplane propulsive sizing. There are two primary types of hydrofoil; fully submerged and surface piercing. Hydrofoils offer a complex control problem as there is a danger of both accidentally over immersing and of the vehicle leaving the water altogether (known as broaching). This height control problem is approached in different ways by the two variations of design. A fully submerged foil system relies on active control from control surfaces mounted on the hydrofoil section due to very little damping in the system as the vehicle changes height (the only component being change in buoyancy as the strut

is immersed or elevated). These must be coupled with an advanced control system and sensor suite. A surface piercing system is composed of a number of lifting surfaces arranged in such a way so as to reduce or increase the wetted lifting area depending on the foil submergence. With careful design this can lead to an automated height and roll control with very little or no active control required from a control system.

A surface piercing hydrofoil solution would seem to lend itself more to the vehicle discussed in this report. However, concerns remain including:

- Structural loads arising as a result of impacting the water at high landing velocity and the sudden lift forces that result.
- Stowage; a surface piercing design would be difficult to stow in a confined space and the mechanism to do so may be significant in order to withstand the loads expected during landing.
- The remaining possibility, even with submerged foils, of losing depth control and porpoising in wave conditions.

While these challenges may be overcome, the focus of this study was to prove the overall feasibility of a submersible aircraft concept. Hydrofoil solutions were considered too high a risk and overly complex at this stage to consider further.

5.3.3 Skis

Skis have been employed before in a seaplane context, namely the supersonic “Sea Dart” built in the early 1950’s. They offer a relatively low drag solution with simplicity being their main advantage over other systems.

Figure 1: *Convair* Sea Dart showing ski deployment

The *Convair* Sea Dart experienced violent vibrations during take-off and landing at 130 knots even in flat water despite careful design of the shock absorbers built into the skis. As the skis do not produce significant lift at low speed, a design incorporating them would require a carefully designed hull to give sufficient wing clearance above the water, especially in any elevated sea state.

5.3.4 Planing hulls

Finally, there is the more conventional planing hull design, either incorporating a monohull into the fuselage design (a flying boat) or through the addition of two or more planing floats (a float plane). This route offers the advantage of being historically well proven. Designs can be optimised for lower drag through the inclusion of one or more steps on the underside of the hull which allow air to be held against the hull surface reducing frictional drag.

A monohull solution incorporated into the fuselage requires careful implementation for the same reasons as the ski or hydrofoil systems, primarily to ensure sufficient wing clearance above the water surface and to minimize the effects of slamming on the large wing surface area.

Floats (or pontoons) allow the underside of the wing to be lifted clear of the water surface and spray, eliminating some of the potential problems found in an integrated monohull design. However, they are not traditionally a stowable solution. For this reason float systems are found more in low speed designs where the large amounts of parasitic drag they induce are more negligible. For a design which submerges this is not viable. Not only would the floats produce crippling amounts of drag but they would also require a ballasting system in order to reduce the large buoyancy forces they naturally produce.

5.3.5 Conclusion to vehicle take-off & landing

The chosen design concept was an inflatable float system, using air-beam technology to provide sufficient structural integrity. This approach will give all the advantages of traditional floats from the perspective of stability, seakeeping, and drag, whilst allowing for retraction to a low volume module to minimize parasitic drag in cruise and submerged conditions. A full description of the sizing process behind this design is given later in this report.

6. Initial vehicle sizing

In order to generate an initial overall concept for the submersible aircraft, an initial sizing exercise was undertaken with the aim of estimating the weight and volume of the vehicle structure, major components, and main systems.

Initial sizing of the vehicle was undertaken through the use of developed Microsoft Excel© spreadsheet tool. As the main emphasis of the project is to investigate the potential design solution space, all sections of the sizing spreadsheet link back to a common set of variables and options, which encompass the key mission requirements and materials options. This approach allows the user to investigate the effect of varying any set of requirements on the overall design weight and size.

The methodology behind the initial system sizing exercise and spreadsheet are found in the following sections which overview the design assumptions made, the calculation and estimation methods used, and the chosen design options for the propulsion system, structure, and electrical system.

6.1 Propulsion systems selection & sizing

This section considers the vehicle power requirements for each operating mode within the CONOP and the matching propulsion requirement and power system. From this, weights and volumes were estimated for the key power and propulsion systems, as well as for the resulting fuel load requirement.

Propulsion was highlighted as a major challenge faced by this design concept. The key questions requiring consideration include:

- How to provide a propulsion system that can provide thrust in the three modes of operation; in air, on the sea surface and submerged;
- Is a common system used across all three modes more desirable than multiple systems matched to individual modes;
- If multiple systems are selected, how are the non-operational systems protected whilst submerged;
- What speeds and ranges are required for each of the three modes of operation?

Of the three operation modes that need to be considered, the airborne mode will require the highest overall power and thrust. For this reason potential airborne propulsion systems were considered first, including; turbofans; turbo-props; pulse jets; rotor system; ducted fans; and solid rocket. Each of these systems was then assessed, not only against its airborne capabilities and features, but also against its potential to provide propulsion for surface and submerged operation modes, and its ability to be successfully sealed if not used when submerged.

It quickly became apparent that turbofans, turbo-props, and pulse jets systems should be considered in more detail.

The following sub-sections described the estimation methods used and the key features of the propulsion systems considered.

6.1.1 Pulse Jets

Pulse jets are of particular interest to a submersible aircraft concept as they have the greatest potential to operate across all three key operating modes. Their simple, no moving parts design makes them practically impervious to submergence removing the complexity, weight, volume and reliability of a sealing system required for conventional air breathing designs.

Pulse jets are split into two main types; valved and valve-less. Both rely on the same basic principle to provide propulsion. Figure 2 shows a simple valved propulsive cycle:

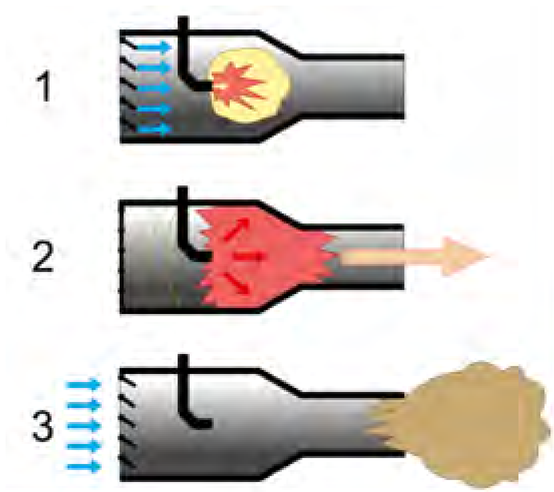


Figure 2: Pulse jet operating principles

With flow established through the inlet, fuel is injected into the combustion chamber and mixes with the incoming air to form a fuel air mixture. An initial ignition source is required to initiate resonance. The combustion gases expand through the nozzle with flow prevented from exiting the intake through feather valves which close as pressure initially increases. Continuous operation occurs through resonating combustion, relying on the flame of the preceding combustion to ignite the next wave.

A valve-less design, shown in Figure 3, operates on the same principles however the shape of the engine itself is used to achieve resonation. The combustion

process creates two pressure wave fronts, one traveling down the longer exhaust tube and one down the short intake tube. By properly 'tuning' the system (by designing the engine dimensions properly), a resonating combustion process can be achieved[2]. In this type of configuration, exhaust is expelled from both intake and outtake and so it is conventional for the intake to be angled backwards to contribute to the thrust generated.

Figure 3: Valve-less pulse jet on test bed[3]

Pulse jets have been used in a number of military applications in the past and were initially developed in the early 1900's. Most famously, they were used in the Second World War to power the German V1 flying bomb (a valved Argus AS 109 unit). Since this time, numerous small scale applications for pulse jets have been designed and flown, almost exclusively as target drones because of the low cost of the engine and its ability to run on almost any fuel. No known valve-less engine has been employed for an airborne design. There is an absence of a real development effort outside of that conducted by amateur societies. The most prominent obstacle for valve-less designs with rear facing intakes in a flying application is that as speed increases the local pressure differential at the intake

reduces the efficiency of the engine, as opposed to a valved design where the increased local pressure at the inlet improves performance.

Valved designs are widely recognized as being difficult to maintain due to the short life of the intake valves. This is expected to be further compounded by their immersion (quenching) in water if used on a submersible aircraft. A valve-less design offers the advantage of no moving parts and also the potential for a change of fuel and continued operation when submerged. The use of a mono-propellant such as the 'Otto' fuel found in the most recent British 'Spearfish' torpedoes would be most likely used for this application.

The advantages offered by a propulsion system capable of air and submerged operation are significant, simplifying and reducing the systems involved for both modes of operation. Disadvantages must also be considered including:

- pulse jets generate resonating thrust, and hence by definition high vibration levels. These may be alleviated by pairing out of phase engines. However, vibration is still likely to be significant;

- acoustic noise levels are extremely high in such engines (122-128dB 100 feet[5] from the engine have been reported). They are normally employed where stealth is not an issue and significant research would be needed to reduce noise to an acceptable level for covert missions;

- radiant heat is also of concern as the glowing combustion chamber seen in Figure 3 illustrates. This radiant heat may not only cause installation issues, but may also be restrictive when immersing in seawater. Careful investigation into potential material options would be required.

- When operating underwater, the use of mono-propellants results in the production of significant volumes of gasses, typically seen as a trail of bubbles. Traditionally mono-propellant designs are used in applications where stealth is not a requirement, i.e. torpedoes. Further research would be required to improve overall stealth.

In order to generate a potential weight and volume for a pulse jet solution a scaling method was employed from test data for an Argus AS109[4], and a US Navy study. The Navy study investigated the application of a valve-less pulse jet as a “Thrust augmented intermittent jet lift-propulsion system”[5] and progressed to numerous prototypes tested on a stationary test bed.

Valved pulse jet sizing from the Argus engine Scaling assumes the length between inlet and exhaust to be the same as that of the original design as it is this length that is critical to tuning combustion resonance and combustion frequency. In this way, increasing the power output of the engine increases the diameter of the combustion chamber. Similarly the fuel mixture ratio is assumed the same as the original as scaling for different fuels is beyond the scope of this project. Scaling is carried out from a thrust coefficient to Mach number distribution digitized from the original report with specific fuel capacity obtained through a similar method. Associated engine accessories such as fuel pumps are scaled from net power. Support mounts and fairing are scaled from engine weight. As the ARGUS is an old engine, and amateur enthusiasts now have significantly more experience in designing valved pulse jets, increases in efficiency are expected over those calculated. These are mainly through the use of thrust augmenters and timed fuel injection. Thrust increases up to 80% are claimed through the use of augmenters and efficiency increases of 10-15% through timed injection[6]. These increases in efficiency are added to the fuel estimate used in sizing. Whilst competitive fuel loads are predicted, the technical challenges of developing inlet valves which are reliable and not susceptible to immersion are considered beyond the state of the art at present.

Valve-less pulse jet sizing: Engine size and fuel consumption were derived from test data[4]. A mid-throttle range thrust coefficient (C_f) was chosen to represent cruise conditions. This value is then used to scale the physical size of the engine in the same manner as the sizing of the ARGUS style engine. As the test results were attained from a stationary test bed, no data exists describing the loss of efficiency as speed increases and so fuel requirement estimates are optimistic.

Data presented in a report from Cornell Aeronautical Test data[7] for a valve-less pulse jet with an intake pointing into the airflow to minimize losses showed reductions in SFC of around three quarters to four fifths of the original value over an increase in speed of 200 feet per second (136mph) . This loss in efficiency essentially discounts the valve-less pulse jet as a possible propulsor for the submersible aircraft.

With further investment and research into inline valve-less pulse jets, the advantages of simplicity and the possibility for a dual fuel system may outweigh the higher fuel requirements, as well as the noise, heat, and vibration issues.

6.1.2 Turbo-fan

Initial research was conducted into turbofans currently available within both military and civilian markets. The selected basis engines were chosen based on an initial estimate for the overall required thrust of between 2,000 lbf and 14,000 lbf. The data for the basis engines selected is summarized in

Table 10 within Annex A

A more detailed estimate of 7,400 lbf of thrust was used for weight and fuel loads. This estimate was made from analysis of data in the CISD seaplane database. It was also assumed for the purposes of sizing that two equally sized units would be used on the vehicle.

The basis engine data was used to create graphs of thrust versus specific fuel consumption (SFC) and thrust versus engine weight. Final fuel weights took into account the variation in power and SFC across each of the discrete segment of the proposed mission profile. An example of the fuel load calculation is shown in Annex A.

The increased SFC at cruise and idle modes was assumed as the worst case for the three stages of flight. This therefore represented a pessimistic fuel burn and

corresponding fuel load requirement. A further 10 % fuel load margin was added to provide further confidence in the estimate. The specifications for the resulting proposed turbofan system are detailed in the Table 4:

Turbofan System	**Values**
SFC [lb fuel/hr/lbf]	0.424
Net Thrust [lbf]	7,400
Engine Weight [lb]	1,610
Fuel Weight [lb]	13,890
Total Weight[lb]	**15,415**

Table 4 Turbofan design specifications

It was assumed that a turbo-fan system would fulfill both the airborne and surface propulsion requirement. Whilst submerged the intake and outtake of the engines would be need to be watertight using torpedo style doors, perhaps using the contraction of the hot engine and surrounding air to provide some internal negative pressure to aid initial sealing.

6.1.3 Turbo-prop

The turbo-prop configuration was considered for its known superior fuel efficiency. Research was conducted into suitable engines currently available within the commercially and military aviation market. A selection of commercially available engines was considered. The basis engine data is shown in

Table 11 within Annex A. Sizing was based on a twin engine arrangement.

Linear interpolation was used on the collected data to estimate turbo-prop characteristics for the submersible aircraft concept. Turbo-props are typically specified in terms of shaft horse power (shp) rather than pounds force thrust (lbf). The link between shp and thrust is complex, depending on factors such as propeller design. For the purposes of initial sizing, therefore, a rough approximation method generally accepted within many engineering discussion forums for steady state flight was used:

$$\text{Power} = (\text{Thrust} \times \text{Velocity (ft/s)}) / 550$$

This equates a power of 3,950 shp to a thrust of 7,400 lbf. An empirically based estimation of weight and fuel load was again calculated from graphs of power versus weight and power versus SFC from the basis engine data with an additional 10% margin added to the fuel. The specifications for the resulting proposed turbo-prop are shown in the Table 5:

Turbo-Prop System	**Values**
SFC [lb/shp hr]	0.43
Power [shp]	3,950
Engine Weight [lb]	1,540
Fuel Weight [lb]	7,470
Total Weight [lb]	**9,010**

Table 5 Turbo-prop design specifications

The turbo-prop design was also assumed to provide both airborne and water surface propulsion. When submerged, the process would, involve a more complex sealing system to protect the prop shaft whilst submerged. For this reason turbo-props were considered unrealistic for the final concept design.

As the propulsion system has a significant impact on the final design layout, it was necessary to avoid down-selecting the system too early in the design process. In order to achieve this, the initial vehicle sizing spreadsheet was designed to output weight and size estimates for each of these three airborne propulsion types.

The key conclusions from the analysis of these options were:

- The pulse jet was considered to be the only realistic potential solution for providing propulsion in all three operating modes due to the inherent simplicity of the system. It is less efficient, perhaps not prohibitively so, and has significant noise, vibration and material issues.

- A turbofan solution provided the benefit of fuel efficiency, speed, relatively compact size and the potential ability to be sealed whilst submerged.

- The turbo-prop was the most fuel efficient solution but was considered to be technologically challenging to fully seal the system.

Based on the key characteristics, performance and fuel consumption calculations, and the aim to develop a feasible concept based on current technology, the final concept for the submersible aircraft utilizes twin turbofans within sealable nacelles for air and sea-surface operating modes, and a single drop-down electrically driven thruster for submerged operations.

6.1.4 Underwater propulsion

The above analysis favored the selection of a more traditional turbofan system for air and sea surface propulsion. However, this then requires a separate propulsion system for submerged operations.

Submerged drag of the submersible aircraft is split into four main components: form drag, frictional drag, induced drag and wave drag. The unconventional shape of the vehicle means that an empirical analysis of these values is impractical. A more theoretical method is required to estimate total submerged drag.

Induced drag is the drag resulting from generated lift. It is assumed that, in submerged operation, the vehicle is trimmed such that the wings are at their zero lift angle of attack. In this mode of operation it can be assumed that induced drag is near zero.

Wave drag is very difficult to estimate without some form of computational fluid dynamic (CFD) code. The unique shape of the vehicle precludes the use of existing resistance codes such as those used within CISD. At the envisaged submerged operating speeds (4 to 6 knots) and corresponding Froude numbers, wave drag is not anticipated to be a dominating component; the main mechanism for wave drag of a submerged lifting body is the formation of transverse waves on the water surface as a result of the pressure distribution around the lifting body. This wavemaking effect has been shown to be negligible[8] at depths greater than two chord lengths. As a result, an explicit estimate of wave drag has not been

used. A 10% margin has been included in the final total resistance to account for this and other minor drag effects.

Form drag is calculated from independent form factors for the lifting bodies (wings) and for the central body (fairing). These calculations are based on the fineness ratio of the center-body (estimated using the maximum cross-sectional area) and the average wing profile thickness[9]. Frictional drag is estimated[10] from a friction coefficient calculated using empirical data for aluminum aircraft at varying Reynolds numbers.

A number of different propulsion options were considered for underwater operation, including pump jets, open screw propellers, and azimuthing drop down pods. Energy options included mono propellants, diesel with air independent plant (AIP), and electric. An all electric solution incorporating a drop down azimuth pod powered by a permanent magnet synchronous (PMS) motor was selected. A PMS motor offers an indicative power dense solution which is well suited for a small scale applications such as the submersible aircraft. Motor weight and dimensions are taken from a commercial unit matching the identified requirements[11].

Of note is the effect of increasing underwater speed on the overall vehicle size. The motor represents the single largest drain on the battery supply and the vehicle resistance essentially has a quadratic relation to speed as shown in Figure 4. It becomes clear that at any speed exceeding 3 knots the battery requirement reaches a size where it drives the design weight.

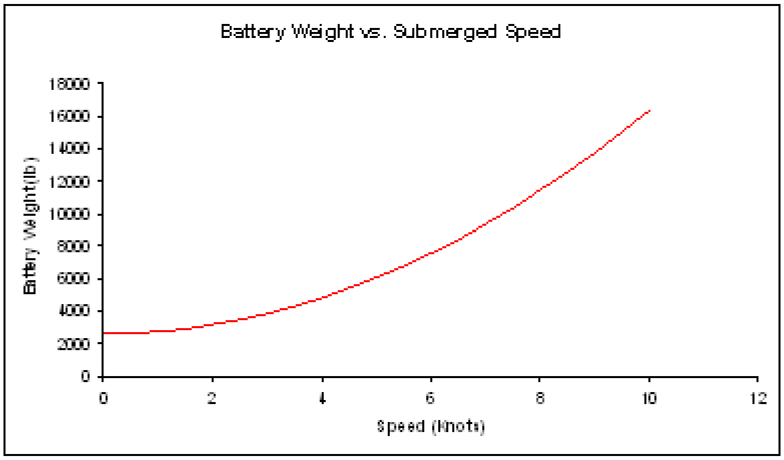


Figure 4: Effect of submerged speed on battery weight

6.2 Structural weight estimation

The structural weight of the submersible aircraft was broken down into three main categories:

1. the pressure hulls for the Special Forces and crew compartments;

2. the wing structure;

3. the structural weight of the fairing.

As wing weight was intimately linked to the wing geometry, this is considered in a dedicated section later in the report.

6.2.1 Pressure hulls

The pressure hull is defined as the compartments containing both crew and Special Forces. Whilst the Special Forces compartment is designed to be free flooding as the vessel submerges, it is still required to withstand crushing loads in the event that it is used as an emergency ballast tank to rise from operating depth to the surface.

Volume requirements were initially estimated based on standard dimensions of Special Forces operatives and equipment. These estimates were then replaced by outputs from computer models of proposed concepts. Cockpit dimensions were

also modeled in a similar manner. More space is allocated for the operating crew as they are expected to remain with the craft for the duration of the mission and require provisions for habitability and more comprehensive stores.

Pressure hull weight is driven by depth of immersion. Greater depths require greater levels of structural integrity and have a corresponding greater impact on structural weight. The assumed maximum operating depth of the design presented in this report is 30m [98.4 feet]. This is significantly shallower than the operating depth of a typical conventional military attack submarine (around 200m [656 feet]). This allows more flexibility in the design of the pressure hulls when compared to the geometry of operating military submarines whose pressure hulls are almost invariably made up of cylinders and hemispheres.

The methodology for a standard, frame reinforced pressure hull consists of analyzing the inter-frame collapse, overall collapse, frame tripping pressures, out of circularity stresses, plate stresses and flange stresses. This is achieved through a combination of empirical curves and stress, and strain calculations. Results from this analysis on a conventional pressure vessel similar in size to that expected for the concept design showed a simple unframed cylinder with a standard hoop and longitudinal stress analysis conforming to thin walled cylinder assumptions was more efficient than its frame stiffened equivalent in terms of simplicity of build and structural weight.

Based on this assessment, the pressure hull shape of both the Special Forces and the crew compartment was designed to minimize the volume of the two spaces and allowed to move away from pure cylindrical and hemispherical restrictions with the assumption that under the expected operating pressures it would be possible to reinforce an irregular pressure hull.

Structural analysis of a pressure hull which is neither cylindrical nor hemispherical is not a straight forward process, normally requiring a computational approach such as Finite Element Analysis. As this approach is not within the scope of this report, a more empirical approach was adopted.

Empirical data[12] relating the dimensions and pressure differentials of aircraft fuselage pressure vessels to structural weight over a large number of aircraft with a large number of pressure differentials is available. As no equivalent collection of data exists for submersible structural weights, this resource was used to estimate the weight of the compartments. Details of this calculation are seen below.

Fuselage weight is based on gross fuselage wetted area, dimensions and a pressure load parameter, for the purpose of these calculations we take the fuselage as the pressure hull being sized.

The pressure index is:

$Ip = 0.0015 \times P \times B$

where:

P = maximum pressure differential (lb / sq ft)

B = fuselage width (ft)

From an empirical analysis of previous design, the fuselage weight is then:

$$W_{fuselage} = (1.051 + 0.102 \times Ip) \times S_{fuselage}$$

The raw data and fitted curve on which this algorithm is based are seen below in Figure 5. The range of Pressure Indexes extends up to just over 40 while those calculated for the operating depths and pressure hull dimensions of the submersible aircraft are around 55.

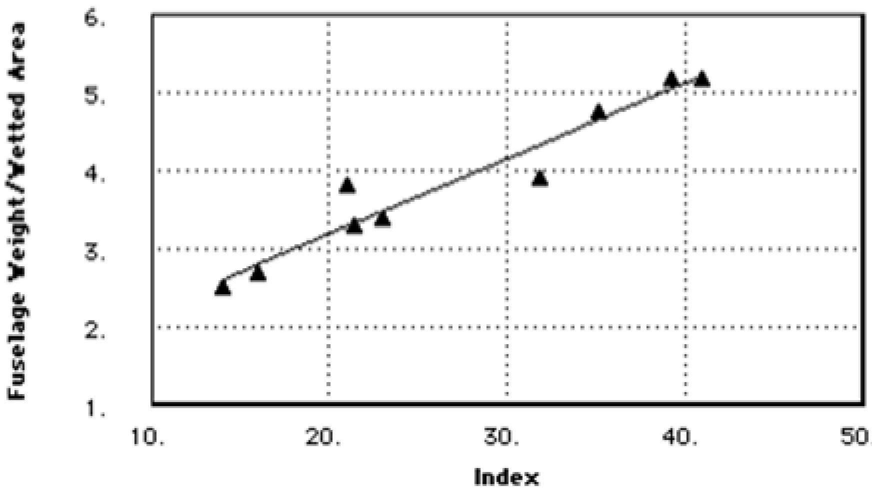


Figure 5: Pressure hull weight/area vs. pressure index

There is some uncertainty in the validity of such an approach due to the operational pressure (and so I_p) being beyond the values seen in the empirical data. However, analysis of the equations given shows the relationship between pressure differential and structural weight to be a linear one for defined pressure hull dimensions which suggests that extrapolation to higher pressure indexes is not unreasonable.

Use of an empirical approach restricts the ability to investigate different material options. Common aircraft grade aluminum is assumed as the material used in the aircraft fuselage data. Without specific details, it is difficult to examine alternative materials with better stress characteristics. As the design progresses and a proper structural analysis can be carried out, the use of materials such as composites, advanced alloys and titanium should be considered. It is recommended that a finite element analysis be used to carry out this study as pressure collapse of irregularly shaped vessels is almost impossible to calculate analytically.

6.2.2 Fairing

In the context of the submersible aircraft design, fairing is considered to be the structure inboard of the wings forming an envelope around the centrally located

systems and compartments. It is assumed to be subjected to free flood conditions and that it is not a load carrying structure

Fairing weight was initially estimated as ten percent of the total structural weight in order to make a first iteration of the design. Once 3D CAD models were produced, a more accurate calculation was made based on the surface area of the fairing and a standard skin thickness from the aircraft practice. A further ten percent margin was added to this weight as with all other weight estimates to allow for growth and the inclusion of any fastenings.

Material selection is variable within the spreadsheet from a database of alloys and composites, as the fairing is not load carrying and its thickness is arbitrarily set at this stage, aircraft grade aluminum was selected for weight estimating purposes over more exotic materials like titanium whose superior structural characteristics are not required. Composites were also rejected due to reservations about the effect of immersion and its impact on any delaminations or imperfections within the construction. Advantages may be offered by such materials and they should certainly be considered in any future more detailed development work.

6.3 Vehicle sub-systems selection & sizing

The assumptions used for the selection of the concept vehicle's sub-systems are summarized below along with a summary of the methods used for initial weight and volume estimation of the selected systems. Data is collected from a number of commercial and military sources.

6.3.1 Heating, ventilation and air-conditioning (HVAC) systems

The heating, ventilation and air conditioning (HVAC) systems for both crew and Special Forces compartments are sized to allow fifteen air changes per hour. Indicative weight and volume estimates are taken from standard units found marketed by a commercial HVAC supplier[13].

As the Special Forces compartment is to be flooded during submerged operation alternative methods may be considered to increase comfort levels during transit.

These may include the addition of water heaters to raise the ambient water temperature whilst submerged. It should be noted, however, that no additional systems were included in the initial weight and volume estimation discussed in this report.

6.3.2 Control systems

Control mechanisms for all three operating modes are considered and offer an interesting design challenge. Simplicity was considered a key driver in initial design because of the free flooding nature of the wing and the implications full submergence would have on a relatively intricate flap or slat mechanism.

A twin flap configuration was adopted to allow roll independent yaw control and eliminate the need for a vertical stabilizer (i.e. a tail and rudder). It is envisaged that the pilot will be assisted by a flight control system acting between the manual yoke inputs and the final flap deflections and that this system should be able to deal with the smaller deflections needed for underwater maneuvering. A Reynolds number analysis shows that the control surfaces can be expected to be around five to six times more effective in underwater operation than in air.

Low speed sea-surface control is expected to be achieved through either differential thrust from the two turbofans and their resulting moments or from a set of float mounted rudders until sufficient speed is reached to make the air control surfaces effective. At this stage a rudder system has not been sized or included in sizing estimates.

In order to reduce the number of moving parts in the control assembly, a fly by wire system was adopted to allow more flexibility in the internal layout and negate the need to route control cables. Indicative actuators were sized from a commercial supplier[14] and their sizes and weights included in the initial sizing estimate.

6.3.3 Ballast system

Ballast tanks are located in the wing, outboard of the fuel tanks, positioned so that wing loading due to fuel is minimized in flight. The ballast tanks are sized to achieve design neutral buoyancy. Neutral buoyancy is defined as the point at which the density of the vehicle is equal to the density of the fluid it is immersed in, in this case saltwater. At this point the vehicle will sit in vertical equilibrium at any depth.

In order to reach this density, all system volumes were estimated and split into internal and external categories. Internal volume is taken as that found inside an already accounted for volume, for example, crew within the watertight crew compartment. They contribute no further buoyancy to the design and only their weight need be considered.

The overall balancing procedure for weight, volume and ballast is seen in Figure 6. An initial estimate is made of the overall weight and volume of the vehicle. This is used to calculate all size dependent elements of the design. The new cumulative weight and volume of all systems is then re-entered, replacing the initial estimate. In order for the design to be considered balanced, the weight and volume must not change from the previous iteration and the ‘resultant buoyancy’ must be equal to zero.

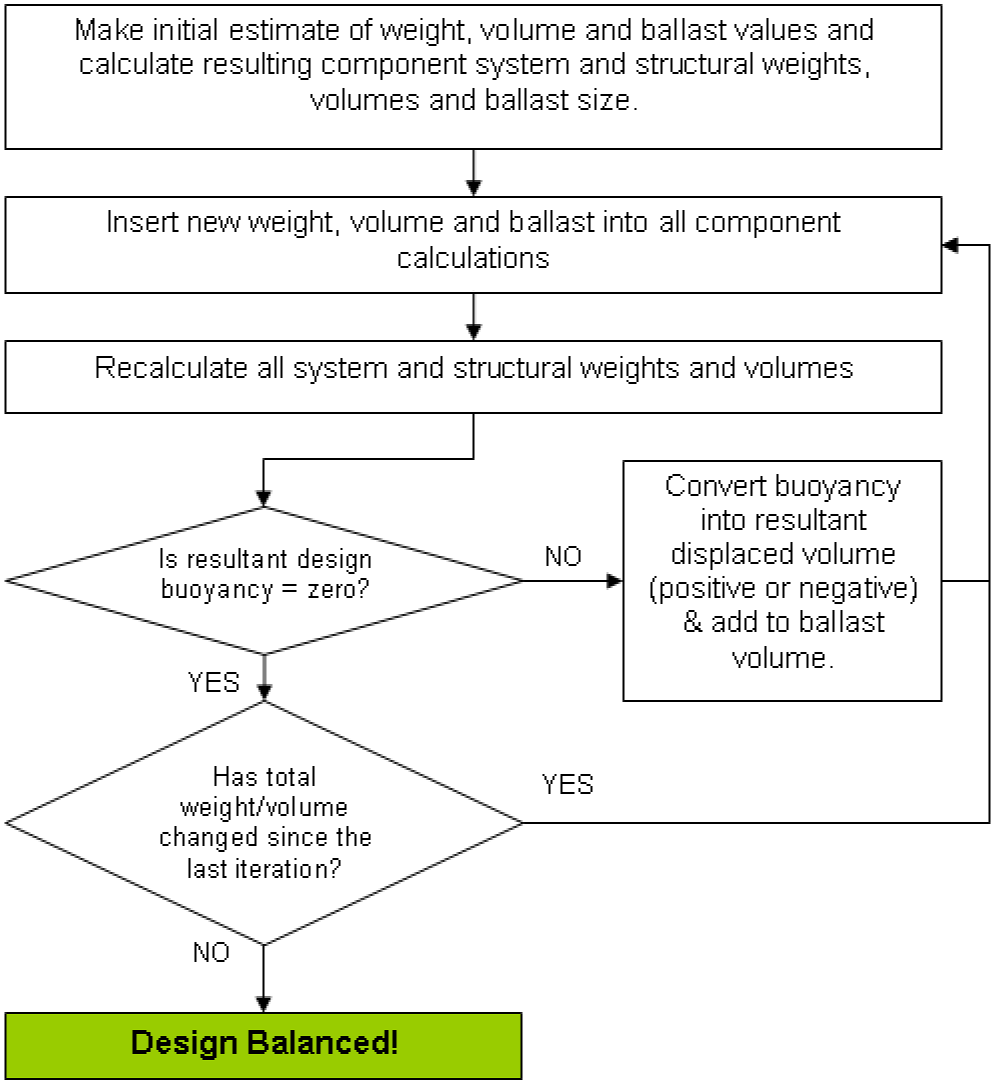


Figure 6: Weight, volume and ballast balancing process

The 'resultant buoyancy' is defined as the total vehicle buoyant force minus the weight of the vehicle. This condition is calculated to account for a set percent of fuel loss over the delivery flight and the weight of the corresponding amount of compensating water in the tanks. It also allows for the free flooding of the Special Forces compartment. A predefined volume within the wing is set aside to contain both fuel and ballast tanks. This is considered to be the watertight section of the wing. If the size of the ballast tanks exceeds this allowed volume, the designer must further reduce system buoyancy or increase weight. The required 'submergence force' is, in this case, calculated to give the designer the option of

using dynamic lift to achieve submergence although this approach is not recommended. Similarly, the 'equivalent mass' is presented to tell the designer how much weight to add to achieve neutral buoyancy.

Examples of these outputs for both an unbalanced and a balanced design are seen in Figure 7 and Figure 8 respectively.

Unballasted and Uncompensated (Metric)			
Weight	191.60	kN	
Displacement	449.94	kN	
Ballasted, Compensated and Flooded (Metric)			
Weight	449.94	kN	
Displacement	449.94	kN	
Required Submergence Force	7.64	kN	
Equivalent Mass	*778.80*	*kg*	Unbalanced
Sufficient Wing Space for Ballast?	No		
Volume of Ballast Exceeding Wing Storage	**27.50**	**ft^3**	

Figure 7: Example of unbalanced design output

Unballasted and Uncompensated (Metric)			
Weight	177.6373	kN	
Displacement	502.1529	kN	
Ballasted, Compensated and Flooded (Metric)			
Weight	502.1529	kN	
Displacement	502.1529	kN	
Required Submergence Force	-1E-05	kN	
Equivalent Mass	*-0.00103*	*kg*	Balanced
Sufficient Wing Space for Ballast?	Yes		

Figure 8: Example of balanced design output

6.3.4 High pressure air system

The high pressure (HP) air system is designed to supply HP air to the ballast tanks when surfacing as well as to the Special Forces compartment to increase freeboard at the surface. It is also sized to supply the inflatable floats with the necessary volume and pressure and to supply breathing air to both Special Forces and crew through a series of regulators.

HP air is expected to be supplied to the vehicle whilst onboard the deployment vessel. An incorporated recharge facility is not deemed necessary as the volume of air required for a standard mission should be easily accommodated within a reasonable volume. An indicative system layout is seen in Figure 9 showing the redundancy levels expected between port and starboard supply and systems.

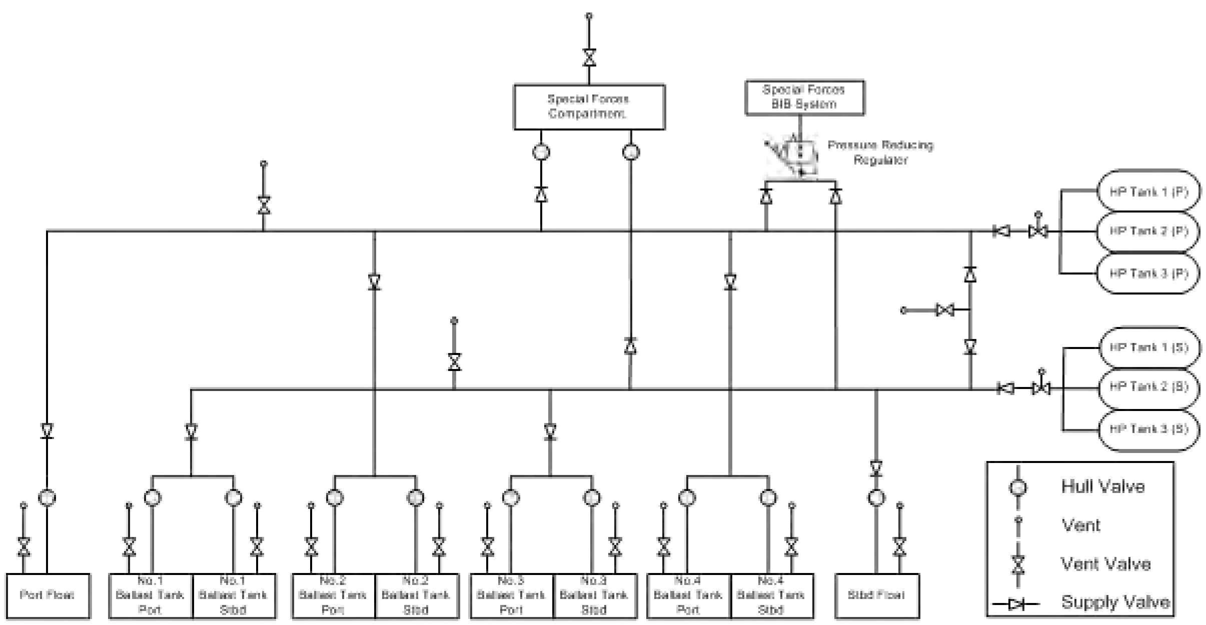


Figure 9: HP system indicative layout

Sizing of the required uncompressed volume is based on the size of the ballast tanks, allowing sufficient air for two ballast evacuations and for four float inflations, with a margin to allow for the small quantity of air required for breathing.

The required volume of air needed to evacuate the ballast tanks is calculated from the operating pressure using Boyle's law.

A higher storage pressure (700 atmospheres) is used to allow the required compressed air to be carried while minimizing system volume. This is done at the expense of system weight. This pressure was assumed achievable based on recent industry reports of advances in composite HP storage systems. A simple thin walled pressure vessel analysis was carried out to estimate the structural weight of containing such a pressure. The equations for which are seen below:

$$\sigma_\theta = \frac{pr}{t} \qquad \sigma_{long} = \frac{pr}{2t}$$

Where:

σ_θ = cylinder hoop stress

σ_{long} =cylinder longitudinal stress

p = storage pressure

r = vessel internal radius

t = material thickness

A safety factor was applied and a number of different materials examined. Grade 5 Titanium was selected for this study. Weight estimates were then made based on the resulting cylinder radii, length and thickness and the chosen material.

6.4 Electrical system selection & sizing

A standard approach was taken in order to size the electrical loads expected of the vehicle. Systems were identified for the four modes of operation (in flight, surfaced, submerged transit and loiter) and approximate power requirements identified. A brief analysis of required operating times for each of the components was made and used in conjunction with the operating powers to size the total power storage requirement.

A battery solution was selected for underwater operation in order to remain covert and eliminate the need for snorkelling. Batteries were sized to provide sufficient power for the in-air and sea-surface modes of operation. Some trickle charging capability is likely to be achievable off the secondary gearbox on the turbo-fan engines. However, this factor was not included in order to offer a worse case for battery system sizing.

The battery pack was sized using ZEBRA battery data. ZEBRA batteries are commercially available molten salt based batteries which offer a relatively high energy density. They have been used in commercial and military applications including submarines and submersibles. Other battery solutions exist with potentially higher power densities that would reduce the overall battery system size and weight. However, the proven ZEBRA design was selected to reduce risk.

An indicative powering layout is shown in Figure 10. The system consists of three independent direct current (DC) power busses for propulsive purposes, Special Forces compartment and crew compartment with each connected to the battery supply via an individual distribution switchboard. These busses are expected to be 24 volt systems with a step down in the crew compartment for 12 volt systems and a transformer and inverter on the propulsion bus to provide 400 volt alternating current (AC) to the synchronous propulsion motor. This approach allows the operator to completely shut off the Special Forces and propulsive power supplies when in loiter mode to isolate the crew compartment and reduce parasitic battery drain.

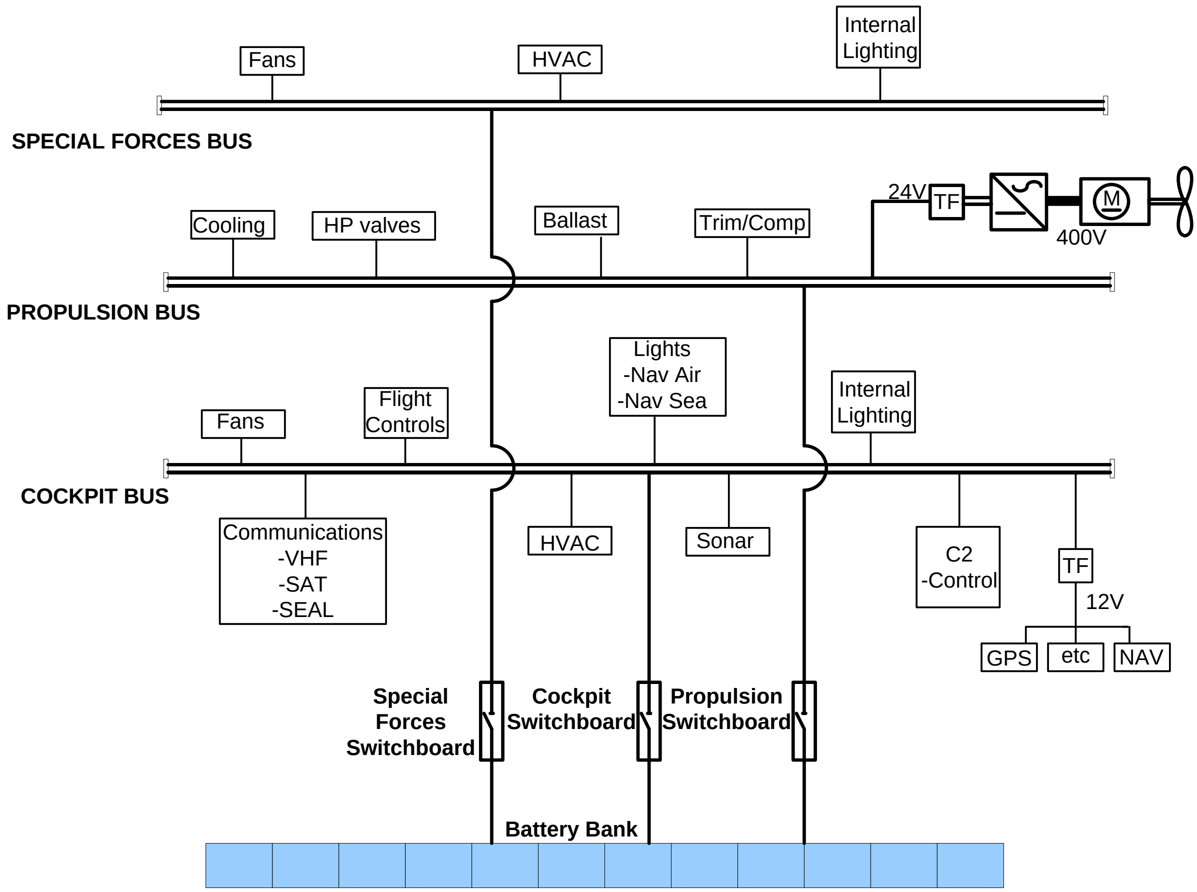


Figure 10: Indicative powering layout

The resulting battery sizes constitute the largest single system weight component in the overall vehicle design, exceeded only by the fuel weight. This highlights that battery power density improvements could have a significant impact on the overall vehicle size.

Future design iterations may consider the use of an additional compact diesel generator with a snorkel system which could be employed during loitering to provide a recharge capability. Whilst this is not an ideal solution in terms of mission flexibility and covertness, battery requirements could be greatly reduced with a corresponding reduction in weight and volume.

6.5 Float system sizing

Inflatable floats offer an interesting design challenge. A trade-off exists between the optimum shape for minimum drag and the optimum structural shape. There is no precedent for the design of an inflatable planing hull of this type and, as such, an approximate method was developed to size the system.

6.5.1 Structure

Floats were initially modeled as air beams, structures which are of increasing interest in both military and commercial applications. The floats were modeled as cylinders with a finite shell thickness whose critical properties are:

Internal pressure	P_i
Radius	r
Length	L
Skin thickness	t
Elasticity Tensor	C_{11}
Young's modulus in warp and weft of the fabric	E_{warp}/E_{weft}
Poisson's ratio in both warp and weft of the fabric	$\upsilon_{warp}/\ \upsilon_{weft}$

From the overall weight of the vehicle, the required displacement to be supported by the two floats was calculated using an appropriate loading factor. From this, a hull length and the corresponding cylinder radius was generated.

The structure was then approximated as simply supported beams under a uniformly distributed load using air beam equations[15]. Approximations were made of the hoop, longitudinal and wrinkle stresses. Hoop and longitudinal stresses were calculated using standard thin walled cylinder approximations. These calculations assumed static, not dynamic, loading.

Wrinkle stress is a critical calculation as it is this stress at which the assumptions on which the analysis was based become invalid. It can be considered as the

equivalent of buckling for inflatable structures. For a given set of properties, the load per unit length to cause wrinkle is seen below:

$$F_W = \frac{4 \cdot \pi \cdot r^3 \cdot P_i}{L^2} \cdot \left(1 + \frac{P_i \cdot r}{2 \cdot C_{11} \cdot t}\right)$$

Where the elasticity tensor C_{11} is calculated as: $$C_{11} = \frac{E_{warp}}{1 - \nu_{warp}\nu_{weft}}$$

A notional material, high tensile *Vectran*, was selected. More detailed material research is recommended if air beam float design is further considered. An internal pressure of 0.1 MPa (14.5 psi) above atmospheric conditions allows a wrinkle load safety factor of 1.5 to be achieved with a correspondingly high safety factor on hoop and longitudinal stress estimates.

Shear loading was considered, but is more difficult to estimate. No satisfactory method for predicting shear loading and its effect on wrinkle stress was found for longitudinal loading. However, a method for predicting the wrinkling stress of an air-beam under transverse loading has been advanced[16]. Following this calculation, it became apparent that, even in this preferred loading state, wrinkling due to shear loading was the most likely failure mode.

Alternative air beam structures are possible as shown in Figure 11. A conventional hull shape may be formed by bending air-beams and arranging them longitudinally along the length of the hull in a rib arrangement so that the effect of shear loading may be minimized. An alternate solution which may be easier to implement is the inclusion of vertical ribs within the air beam itself, angled to transmit the shear loading to the support point and convert it into a tension. By its nature, it is easier to manage. Another alternative may be the incorporation of a toughened skin (such as the fairing material) on the base of the float, possibly to then be incorporated into the float storage area when retracted. This could attach more solidly to the fore and aft support points to transmit the shear directly into the structure and around the air-beam. These approaches have not been modeled,

and hence, the weight estimates reflect a set of air-beams with the skin thickness, internal pressure and dimensions to meet the static loading conditions described above.

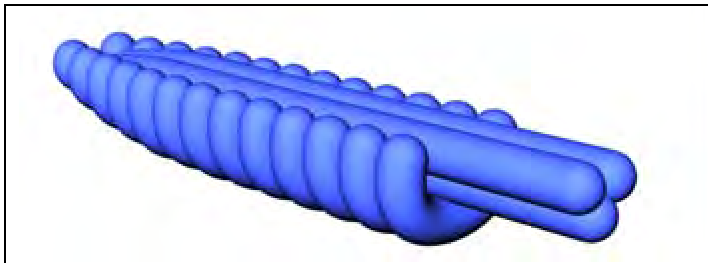
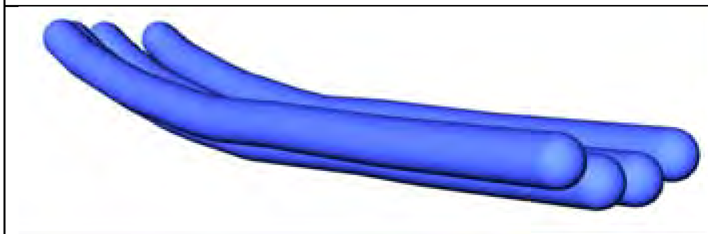
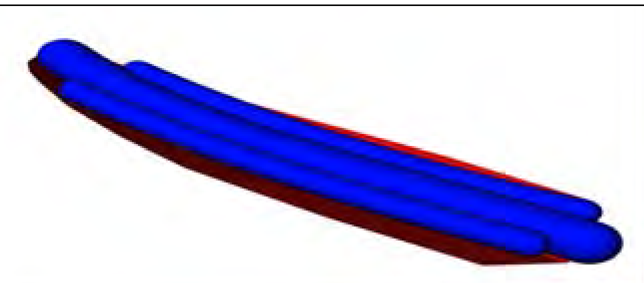
	*Transverse Air-beams*
	*Longitudinal Air-beams*
	*Air-beam Plus Shell*

Figure 11: Potential air-beam arrangements

Weights and volumes were calculated using the material properties of *Vectran* and the wall thickness calculated from the stress calculations. Air requirements to inflate the hulls was included in the high pressure air system. A packing density of 150% of material volume was used to estimate the storage volume of the deflated floats.

6.5.2 Form

The analysis assumed that the choice of air-beams did not restrict the shape and hydrodynamic form of the float design. In reality this is unlikely to be valid and will require further consideration in further design iterations.

As this study was focused on creating an initially viable submersible aircraft design, it was considered inappropriate to optimize the planing characteristics of the floats. A simple existing float shape was scaled to fulfill the volume requirements. As with most seaplane planing surfaces, the design includes a step on the underside of the hull in order to reduce frictional drag through ventilation of hull sections behind the step.

Drag was estimated using the *Savitsky* resistance prediction method, based on an estimate of the lifting surface dimensions. This allowed shear force estimates to be made and provided reassurance that the powering estimate taken from the seaplane database was representative. The values determined through this method were considered a worst case in that they did not take into account the presence of the step, the lift of the wing, or the effect of trim. In reality the initial increase in trim angle of the hull would linearly increase the lift being produced by the wing and so reduce hull draft, albeit at the expense of induced drag from the wing.

7. Wing design

Unlike a conventional aircraft wing design, the design of the submersible aircraft's lifting surfaces must not only be optimized for air performance but also factor in the effect on submerged operation. Key design drivers were expected to include:

1. **Internal Volume -** As the majority of sub-systems are enclosed within the wing in free flood conditions, there is a requirement for a high internal volume;

2. **Zero Lift Angle -** Underwater operations dictate the need to minimize induced drag; to do this, the wing should have a zero lift angle as close to zero degrees as possible and should not rely on parasitic lift to maintain trim (e.g. a tail providing downward lift);

3. **Surface Area –** While submerged, the main drag component is likely to be frictional. The design should attempt to minimize surface area;

4. **Wing Area –** High lift devices have been discounted in order to reduce the complexity and scale of systems susceptible to immersion in salt water. This has been done at the expense of wing area and drag;

5. **Structural Design -** The design should be robust enough to deal with the very high wing loading that could occur when operating underwater due to the significantly higher Reynolds numbers experienced;

6. **Wing Loading -** Take-off and landing speeds are critical factors in the design, particularly when sizing power systems and floats. It is beneficial to minimize these speeds. This can be achieved by designing for a relatively low wing loading. Secondary effects include improved maneuverability and responsiveness. It will also result in larger wing surface areas and submerged frictional drag, resulting in the need for compromise.

For these reasons, tailless delta wing design with some blended wing body characteristics was adopted. This approach gives excellent internal volume characteristics whilst minimizing surface area. Structurally, a delta design gives superior strength over a more

conventional wing fuselage combination with wing root stresses reduced by the larger root chord.

A tailless design requires sweep to achieve longitudinal stability. One effect of sweep is to increase span-wise flow along the wing, particularly at low speed. The resulting up-wash, increasing in strength along the span, leads to increasing local angles of attack. At low speed, this flow characteristic can lead to the tips of the wing stalling before the inboard sections, making the aircraft pitch up and potentially stall. In order to combat this, an outboard wing section with lower sweep than the inboard sections was included in the design. This should decrease the up-wash and local angle of attack at the tip and move any stall inboard resulting in a nose down response to stabilize the stall.

The approach used is similar to that previously used to design the CISD flying wing Advanced Logistics Delivery Vehicle[16].

7.1 Wing loading

To start the wing design process, an initial wing loading value was selected. Seaplane wing loadings are traditionally lower than those of conventional aircraft due to the requirement for lower take-off and landing speeds. An empirical approach based on seaplane maximum take-off weights (MTOW) and corresponding wing loading values was used. The seaplane database compiled by CISD was used to create plots of these two variables and fit a linear distribution. By this method a suitable wing loading of 130 kg/m^2 [0.205 lb/ft^2] was estimated.

7.2 Stability and trim

The most significant design challenges when considering a tailless aircraft are trim and stability. An aircraft can be considered trimmed if, during steady flight, there are no resulting moment forces about any axis. A stable aircraft will have a tendency to return to this trimmed state after a disturbance from a gust or change in angle of attack.

7.2.1 Longitudinal static stability

In order for a design to be longitudinally stable, it must produce a nose down moment about its center of gravity in response to an increase in angle of attack, restoring the aircraft to equilibrium.

This is most simply achieved by placing the center of gravity in front of the aerodynamic center. The aerodynamic center is defined as the point on the wing through which lift can be considered to act. When the aircraft experiences an increase in angle of attack, the resulting lift (acting through the aerodynamic center) increases resulting in a nose down moment about the center of gravity. The moment arm between gravity and aerodynamic center becomes critical to the handling of the aircraft. A large moment results in high sensitivity to changes in angle of attack and the aircraft will attempt to return too quickly to equilibrium, potentially inducing oscillations. If the moment is too small, the vehicle will be too slow to return to equilibrium and response will be poor.

Static margin is used to quantify this characteristic. Static margin is defined as the distance between center of gravity and aerodynamic center divided by the mean aerodynamic chord. Different texts give different recommendations for static margin values, normally ranging between 4 % and 10%. The wing design process implemented aimed for a wing configuration giving a static margin of around 5%[17].

As center of gravity is determined mainly by the internal arrangement, it is more effective to change the aerodynamic center in order to meet static margin requirements. This is achieved by varying sweep angle, aspect ratio and taper ratio. It also affects the overall center of gravity as ballast and fuel tanks change position. The wing design spreadsheet also allows the user to change the proportion of lift produced by the inboard and tip sections of the wing. This can also be used to manipulate the static margin. An example of a solution from the wing design spreadsheet is shown in Figure 12.

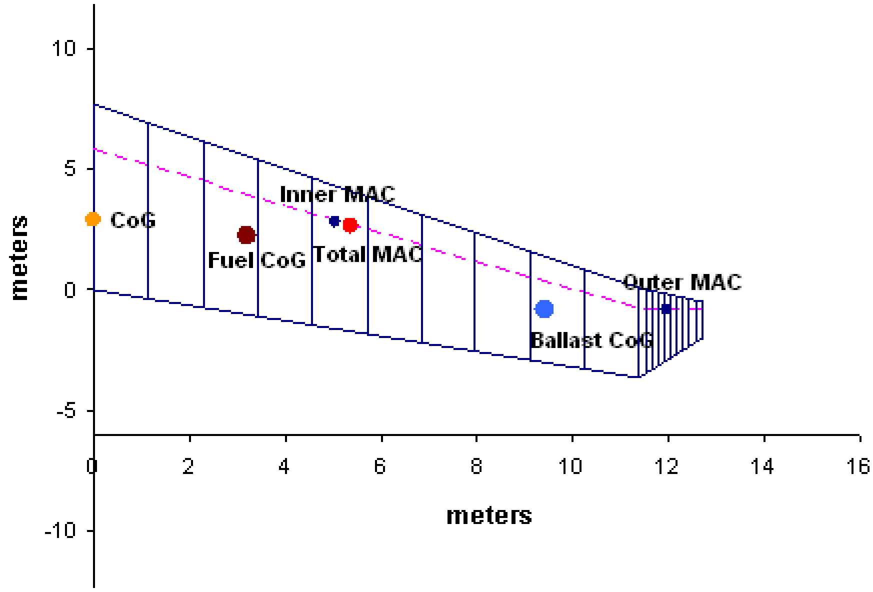


Figure 12: Example of wing design tool output

7.2.2 Longitudinal trim

While the locations of center of gravity and aerodynamic center give a measure of the stability of the vehicle in flight, they do not however guarantee equilibrium in cruise, i.e. trim. A static margin by its nature results in a moment arm about the center of gravity which needs to be compensated for in order for trimmed flight to occur. In a conventional tailed design this is usually achieved through airfoil selection and the use of a tail providing downwards lift and, hence, a countering moment to that produced by the lift acting through the aerodynamic center.

In a tailless design, a counteracting moment must be achieved through airfoil selection and twist alone. Most conventional airfoil sections have a ‘C’ shaped camber line, as shown in Figure 13, providing a negative moment coefficient. This means that the airfoil section produces a nose down moment in steady flight. This moment increases as lift increases. In a tailless design, reflex airfoils are employed as they produce the opposite moment characteristics. Reflex sections have an ‘S’ shaped camber line which results in a positive moment coefficient. In steady flight, they produce a nose up moment which can be used to counteract the

nose down moment that occurs as a result of the static margin.

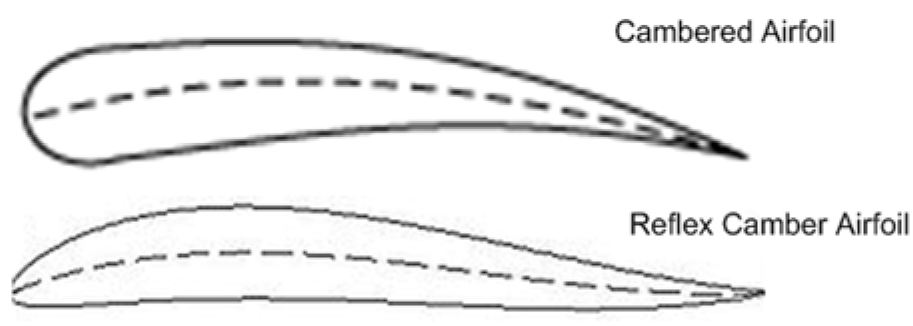


Figure 13: Cambered and reflex camber airfoils

7.3 Airfoil selection

Centerbody airfoil selection is based almost entirely on arrangement. A section which provides sufficient internal volume to house the pressure hull and associated systems is necessary. A NACA 4-digit symmetrical section with its control points distorted was selected to provide the required volume. It is assumed that this central section of the wing does not contribute to overall lift although it is expected that this is not the case. It is also assumed that this section produces no moment as it is symmetrical.

Candidate wing airfoil sections were selected which meet a series of requirements:

- Lift/Drag maximum occurs at design C_L (first approximation $C_L \approx 0.5$);
- $C_d \approx C_{D0}$ (for flying wing, $C_{D0} \approx 0.01$);
- C_{M0} as close to zero as possible to make the aircraft easier to trim when submerged;
- Airfoil designed for intended Reynolds number (Re $\approx$ 15 million);
- Thickness to chord ratio ~ 15% (maximize lift in low speed flight, without encountering separation);
- Zero lift angle approaching zero to ensure submerged trim angle is low.

Airfoils were selected from a number of sources and analyzed using the 2D panel method airfoil analysis code '*XFOIL*'[18]. Taking as an input airfoil coordinates from the UUIC Airfoil coordinate database[19], zero lift angles and corresponding values for moment coefficient were generated as well as lift and drag distributions. The resulting airfoils selected for consideration are seen in Table 6.

Airfoil	Zero Lift Angle	Zero Lift Cm	Zero Lift Cd
E182	-0.482	0.003	0.00483
E184	0.304	0.00242	0.00584
E186	0.790	0.0458	0.00481
E228	0.243	0.0120	0.00463
E230	1.552	0.0495	0.00479
EH159	-0.626	-0.0001	0.00511
EH2010	-0.832	0.0002	0.00520
EH2012	-0.852	0.0002	0.00525
MH45	-0.636	0.0009	0.00471

Table 6: Candidate airfoil sections

Airfoil selections are needed at the root chord, mid chord and tip chord.

In order to down-select to a final set of airfoil sections, a slightly different approach to traditional design methods was chosen. Linearly varying twist along the span of the wing (washout) is often used in tailless wing designs to counter tip stall and to ensure zero moment coefficients at cruise. Drag is increased dramatically where high levels of washout are required. As tip stall is countered by a lower sweep wing tip, the design used zero twist for proper trim.

This was implemented through the *Panknin* Twist Formula, shown below, which is widely accepted within the flying wing community. Tip section is assumed to be the same as the mid-span section. Combinations of root and mid-chord sections were varied until a combination was found which offers near zero required twist indicating a trimmed design.

$$\alpha_{total} = \frac{\left(k_1 * C_{MRoot} + k_2 * C_{Mtip}\right) - C_L * St}{1.4 * 10^{-5} * \lambda^{1.43} * \gamma}$$

$$\alpha_{geo} = \alpha_{total} - \left(\alpha_{L=0root} - \alpha_{L=0tip}\right)$$

Where:	b	=	wingspan
	t_{root}	=	root chord
	t_{tip}	=	tip chord
	t	=	mean chord
	l	=	aspect ratio
	U	=	angle of sweep at quarter chord line
	Γ	=	taper ratio
	k_1	=	$1/4 * \left(3 + 2\Gamma + \Gamma^2\right) / \left(1 + \Gamma + \Gamma^2\right)$
	k_2	=	$1 - k_1$
	$\alpha_{L=0root}$	=	root section zero lift angle
	$\alpha_{L=0tip}$	=	tip section zero lift angle
	C_{Mroot}	=	moment coefficient of root section
	C_{Mtip}	=	moment coefficient of tip section
	C_L	=	design lift coefficient
	St	=	stability factor (static margin)

7.4 Structural estimate

An empirical approach is taken to estimate the structural weight of the wing[20]. This approach is not specifically tailored for a tailless aircraft. However, it is sufficiently accurate for an initial weight estimate with a 10% design margin included. The estimate uses the wing geometry, take-off weight and load factor (where load factor takes account of maneuvers where forces on the wing exceed those required for level flight).

Design limit normal maneuvering load factor is calculated in accordance with FAA Federal Aviation Regulations (FAR)[21] as:

$$n_{\lim it} = 2.1 + \frac{24{,}000}{\left(W_{to} + 10{,}000\right)}$$

Where: W_{to} is maximum take-off weight

Wing structural weight is then given by:

$$\frac{W_{wg}}{W_{zf}} = 0.0017 n_{ult}^{0.55} t_{r,\max}^{-0.3} \left(\frac{b}{\cos\Lambda_{c/2}}\right)^{1.05} \left(1 + \sqrt{\frac{6.25\cos\Lambda_{c/2}}{b}}\right) \left(\frac{W_{zf}}{S}\right)^{-0.3}$$

Where: W_{wg} = Wing weight

W_{zf} = Zero fuel weight

n_{ult} = Ultimate wing loading = $1.5 n_{limit}$

$t_{r,max}$ = Wing root maximum thickness

b = Wing span

$\Lambda_{c/2}$ = Wing sweep defined at half chord

S = Wing area

Wing volume is calculated by taking the cross sectional areas of each of the airfoil sections and numerically integrating between them to take into account the effect of the linear lofts that form the wings outer surface.

7.5 3-D panel vortex analysis

A 3D-vortex lattice program capable of flexible wake modeling was used to study the characteristics of the designed wing. The program chosen was *Tornado*, developed at the University of Bristol in the UK. *Tornado* is based on a standard vortex lattice theory.

The vortex lattice method was developed from the potential flow theory. It is a simplification of the viscous flow experienced in nature around a body such as an airfoil. While simplified, it is considered capable of providing a good indication of the wing properties when designing in a concept design stage. Tornado can support a variety of wing geometries including details such as swept, tapered, cambered, twisted and cranked wings with or without dihedral. It has the capability of utilizing control surfaces such as canards flaps, ailerons, elevators and rudders. It can also output an array of output data including 3D forces acting on each panel, aerodynamic coefficients in body and wind axes, stability derivatives with respect to angle of attack, and angle of sideslip and angular rates.

Tornado is capable of solving the varying wing geometries by modeling all lifting surfaces representing them as thin plates. The code is implemented in MATLAB and distributed according to the GNU-open license protocol.[22]

The submersible aircraft concept design was developed into two potential layouts as shown in Figure 14. Arrangements 1 and 2, are both discussed further in the general arrangement section. Both designs were modeled based on the airfoil selections generated from the wing design Excel spreadsheet discussed earlier.

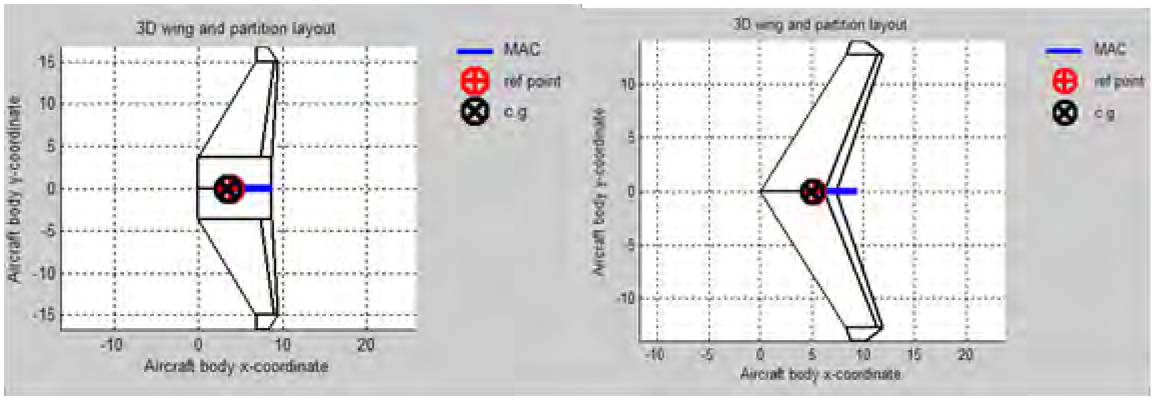


Figure 14: Arrangement 1 (Left) & Arrangement 2 wing geometries

After inputting the wing geometry definitions into *Tornado*, it was possible to alter properties of the wing, such as the center of gravity, calculated from the design tool. The airfoils selected using the *Panknin* Twist formula were stored in *Tornado* and recalled during the wing geometry set up. Once satisfied with the geometry, a flight state was set.

The flight state sets the angle of attack, angle of sideslip, rotational angular rates, and the true airspeed. Sideslip and angular rates were set to zero. The angle of attack was adjusted for both models to achieve the required lift. The required angle of attack was set to 3 degrees to provide 185 kN [41,590 lbf] and 205 kN [46,086 lbf] in lift force respectively for both Arrangements. The true air speed for both cases was assumed to be cruise speed defined in the requirements of 200 mph.

The program automatically generates a free flowing wake lattice and outputs a range of numerical and graphical data, an example of which is show in Figure 15.

Tornado Computation Results

JID:	777	Downwash matrix condition:	20.5625		
Reference area:	145.6057	Supersonic flow warning:	0		
Reference chord:	5.5591	Reference point pos:	5.2676	0	0
Reference span:	27.94	Center of gravity:	5 0 0		

Net Wind Forces: (N)		Net Body Forces: (N)		Net Body Moments: (Nm)	
Drag:	2152.3387	X:	-7429.0732	Roll:	2.2783e-010
Side:	-8.8818e-014	Y:	-8.8818e-014	Pitch:	107245.1269
Lift:	183018.7683	Z:	182880.5921	Yaw:	-1.0147e-011

CL	0.20522	CZ	0.20506	Cm	0.021632
CD	0.0024134	CX	-0.0083301	Cn	-4.072e-019
CY	-9.959e-020	CC	-9.959e-020	Cl	9.1432e-018
$CD_{trefftz}$	N/A				

STATE

α [deg]:	3	P [rad/s]:	0		
β [deg]:	0	Q [rad/s]:	0	Rudder setting [deg]:	0 0
Airspeed:	100	R [rad/s]:	0		
Altitude:	0	PG Correction:	0		
Density:	1.225	Mach:	0.29386		

Figure 15 *Tornado* computational results for Arrangement 2

Several key properties have been calculated including the pitch moment coefficient, lift coefficient and drag coefficient. The aim was to achieve a moment coefficient (C_m) as close to zero as possible. The residual small positive moment value achieved is expected to be counteracted by the moment due to engine thrust or through minor design refinement, hence, the vehicle should be easy to trim in flight. Values for the coefficient of lift C_l = 0.205 and the coefficient of drag C_d = 0.0024 are computed, verifying the initial selection criteria.

The output generated from *Tornado* in graphical format also included:

- Delta pressure coefficient distribution;
- Span load on main wing;
- Local C_l on main wing;
- Bending moment on main wing;
- Shear force on main wing;
- Coefficient dependencies on angle of attack;
- Induced drag polar;
- Polar lift curves;

All of the above can be found in Appendix B for both concepts.

Further detailed analysis of the results generated by *Tornado* should be undertaken. At this stage of the design, *Tornado data* was used only to verify the initial design and airfoil selection. Further work should include analysis of the control and stability derivatives to provide information on how particular forces and moments on the wing design change as parameters such as airspeed, angle of attack and altitude vary. The control and stability derivatives allow the equations of motions to be linearized, hence, the stability of the vehicle can be more readily analyzed.

8. General arrangement

With initial weights and volumes calculated, a 3-D CAD model was produced containing all the vehicle's component systems. This model allowed a number of different arrangements to be generated along with the resulting center of gravity for each. In turn, this data was then re-processed through the wing design process and the trim analysis.

This process is an iterative one as shown in Figure 16. The layout drives the pressure hull and fairing structural weights. The ballast and fuel tanks are located in the wing. The wing design is dependent on the center of gravity which, in turn, is affected by the location of these tanks.

The greatest obstacle in arriving at an acceptable arrangement is the varying center of gravity requirement across the three modes of operation.

In flight the center of gravity must be positioned so as to provide the correct static margin in relation to the center of aerodynamic lift of the wing. There must only be small variations in this value as fuel is consumed to maintain stability on the return flight.

On the surface the center of gravity must be located so as to provide correct trim relative to the center of planing lift. It is also critical to the design of the floats to ensure satisfactory sinkage and trim during the transition to planing during take-off.

As the ballast tanks are flooded and the Special Forces compartment is allowed to free flood, the center of buoyancy changes position relative to the center of gravity. This is perhaps the most critical mode of operation as small variations between the longitudinal positions of the center of buoyancy and center of gravity can result in a large trim moments. It is important that any design minimizes the range of change in transverse center of buoyancy relative to center of gravity. Failure to do this may result in large list angles when the vehicle is submerged. This is also important in loiter mode as a tether solution is expected to be deployed. Large trim moments would result in uneven loading on the tether and increase the risk of losing hold in tidal currents.

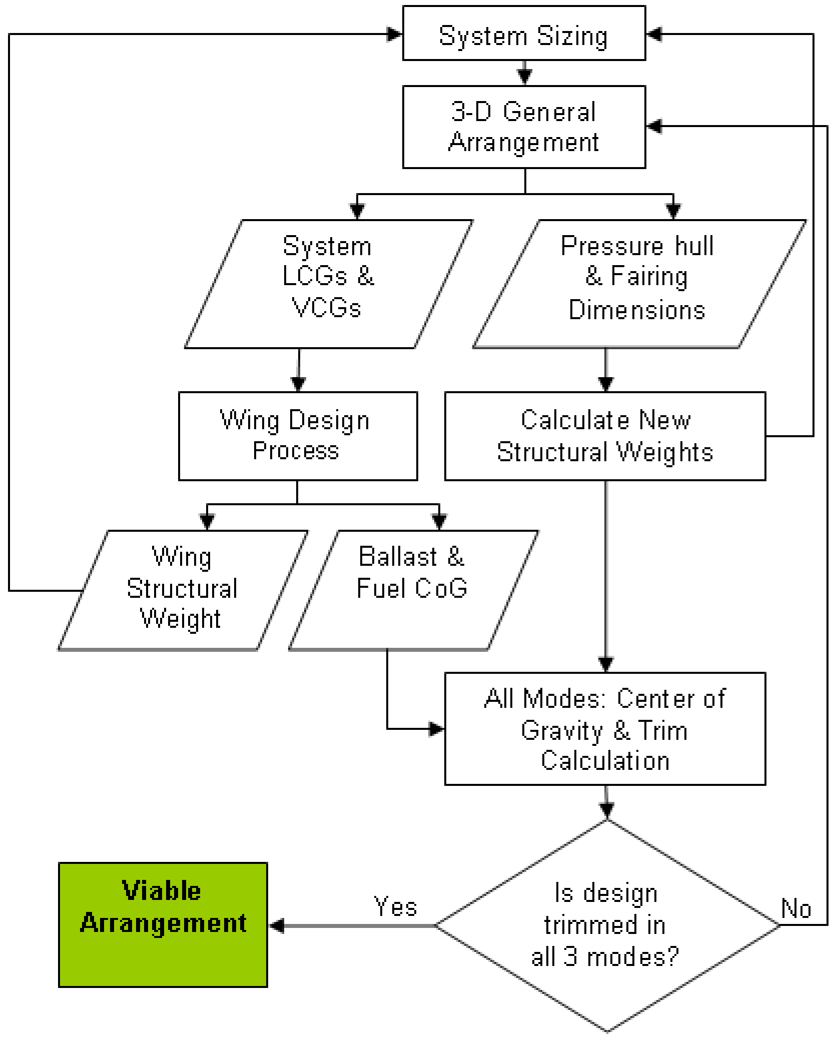


Figure 16: General arrangement process

Trim calculations were made for four trim cases for each arrangement:

1. In flight/surfaced, empty ballast tanks and full fuel tanks;
2. Ballast flooded, flooded wing tanks and fuel tanks at 65% capacity
3. Ballast and Special Forces compartment flooded, Fuel tanks at 65% capacity
4. Worst case design loading, flight mode, no Special Forces, fuel tanks at 10%

The moment arm between the center of gravity and center of buoyancy for each of these trim cases is presented in the following sections. The worst case scenario of having to return to the operating vessel without the Special Forces team and minimal fuel

represents the center of gravity operational limit. A realistic static margin was maintained in this configuration as well as in normal flight mode.

Common to both designs is the cockpit arrangement, shown in Figure 17, which is designed to house the two operators for the duration of the operation. This space not only has to house the avionics suite and flight controls, but also provide sanitary facilities and a space to sleep. As it is the single largest buoyant body in the vehicle, volume was minimized to produce a compact arrangement.

A reclining seat is provided for sleeping. A chemical toilet is located aft of the reclining seat.

Crew compartment volume is compared to that of other extreme endurance vehicles such as the *Rutan Voyager* and the *Apollo* space capsule in

Table 7. Volume per person of the submersible aircraft is greater than the other vehicles even though mission duration is shorter.

The two arrangement options discussed in the following section offer alternative methods for meeting the center of gravity requirements. The two alternative arrangements result in weight differences of 2,500 lbs (7%) and wing span differences of 17 ft (18%).

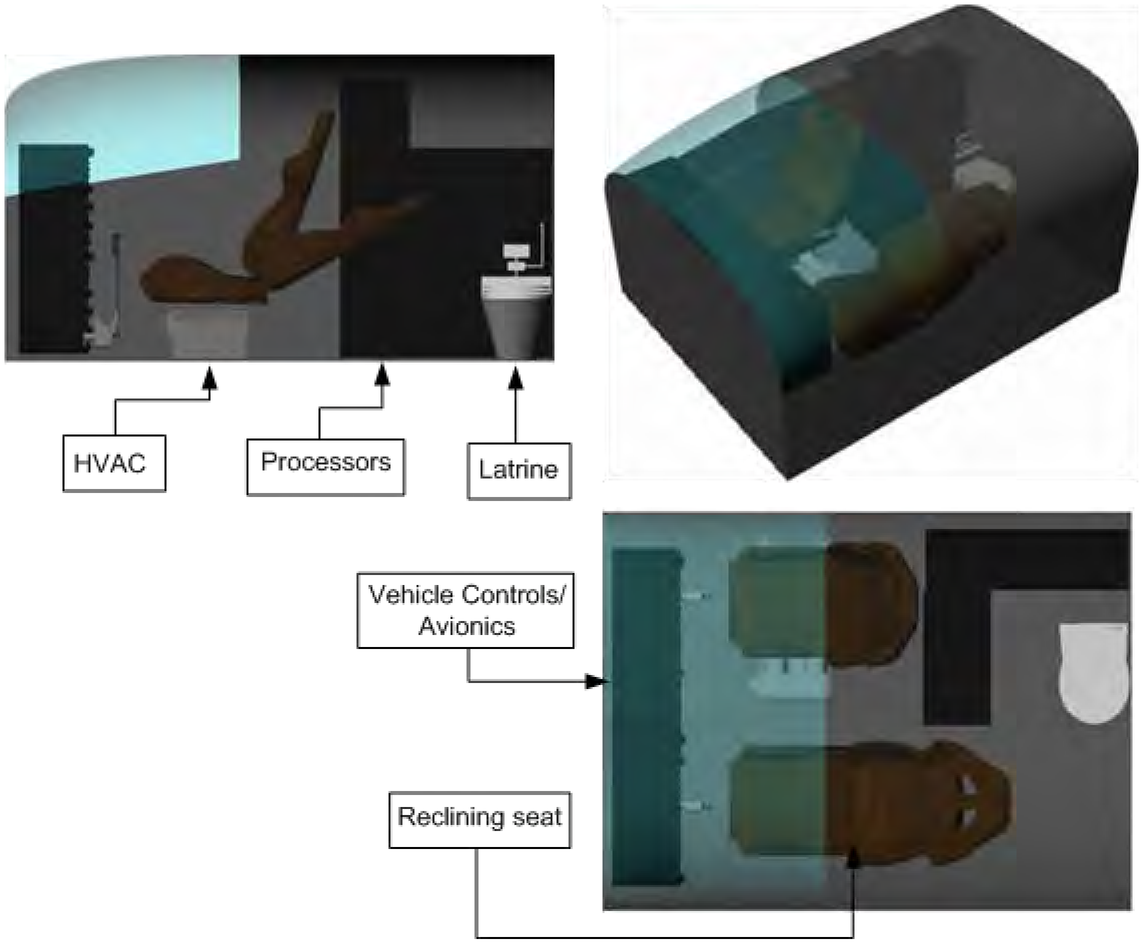


Figure 17: Cockpit arrangement

	Rutan Voyager	**Apollo Capsule**	**Submersible Aircraft concept**
			
Crew	2	3	2
Mission Duration (hrs)	216	144	84
Volume (ft^3)	**35**	**216**	**180**

Table 7: Extreme endurance vehicle volume comparison

8.1 Arrangement 1

Arrangement 1, seen in Figure 18, places the Special Forces in a single compartment forward of the crew compartment. As the crew compartment constitutes the single largest buoyant body, this was placed as near to the center of gravity as possible.

Pilot visibility is through a canopy protruding above the upper surface of the wing. This may prove restrictive during submerged operations. Use of sensor suites such as medium range sonar is envisaged to provide situational awareness when underwater.

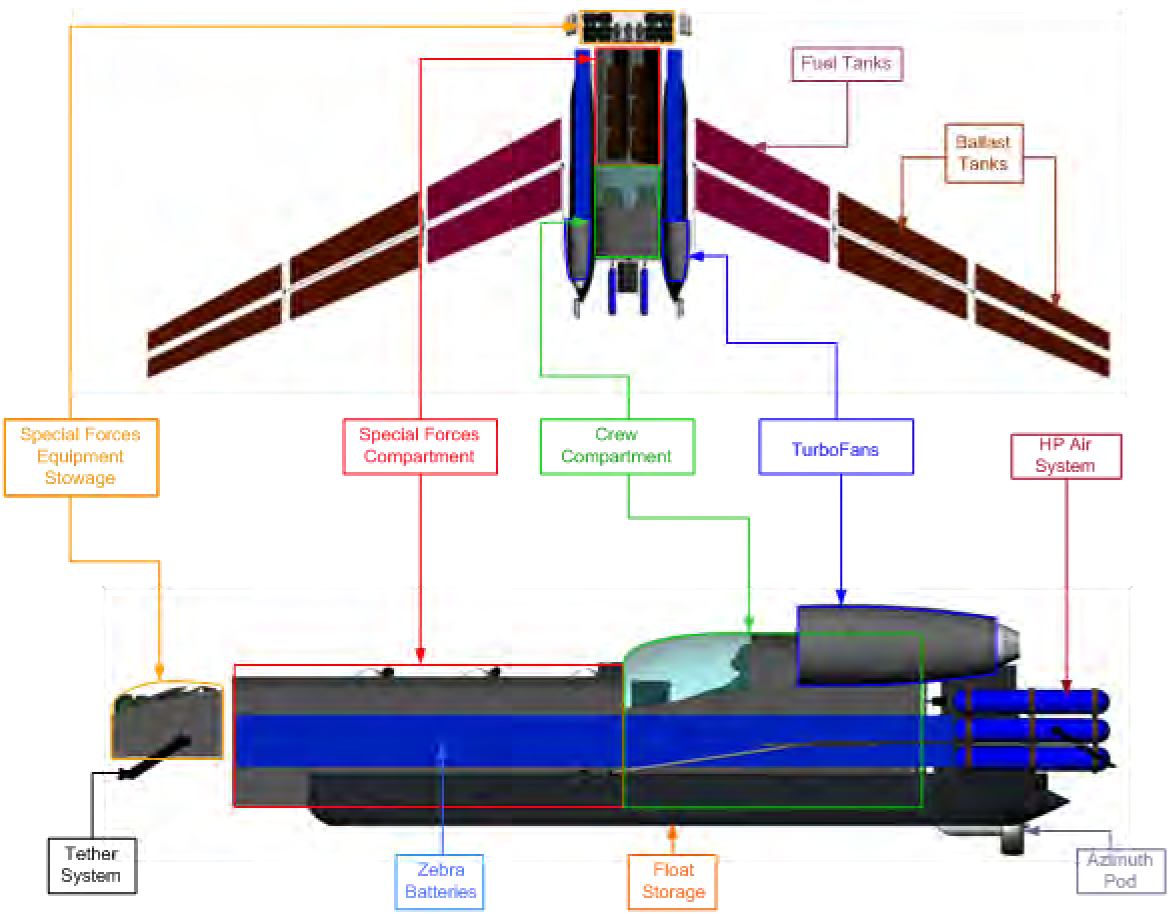


Figure 18: General arrangement - Arrangement 1

Special Forces deployment is through a large hatch set into the upper surface of the center section of the wing to allow an unobstructed exit onto the top of the vehicle close

to the equipment locker. The locker accommodates SF back-packs, equipment and diver scooters.

The two turbofans are located as near to the chord line as possible to simplify control across the expected speed range and to minimize cross sectional area. They are positioned sufficiently aft so as to avoid spray from the floats during take-off and landing. The two units are positioned as near to the centerline as possible although limited by proximity to the cockpit. Tests will be needed to investigate the effect of failure of one engine and the resulting yaw moments.

The batteries are positioned either side of the crew and Special Forces compartments. These, and all the other systems not located in the crew compartment, are subject to free flood conditions and will require adequate sealing and water-proofing.

Fuel and ballast tanks are located around the center of the wing with fuel tanks located inboard of ballast to minimize loading on the wing structure when in flight. The tanks are split into eight ballast and four fuel tanks giving the operator the ability to shift center of gravity. The tanks will contain additional baffling in order to minimize free surface effect.

The azimuth pod and high pressure air system are located aft of the crew compartment. Both of these systems are subject to free flood condition and would need to be suitably sealed.

Figure 19 shows the corresponding wing plan with Table 8 detailing the wing’s principal particulars.

Figure 19: Arrangement 1 wing layout and profile

Principle Particulars	
Weight	36,420 lbs
Wing Span	92 ft
Length	36 ft
Main Wing Sweep	30 degrees
Tip Sweep	0 degrees
Main Wing Taper Ratio	0.49
Tip Taper Ratio	0.4
Station 1 Airfoil Section	EH2010
Station 2 Airfoil Section	E186
Station 3 Airfoil Section	E186

Table 8: Arrangement 1 – wing principal particulars

Wing panels are interpolated lofts between the local root and tip airfoil sections with no twist along the length. Sweep is measured from the quarter chord according to convention. Taper ratios are the ratio between root and tip chords.

With this configuration, it was possible to place the center of gravity very close to the center of buoyancy (a moment arm of 1.2 inches). In normal flight configuration, a suitable static margin was achieved with a main wing sweep angle of 30 degrees. However, it was impossible to find a wing configuration that provided an acceptable static margin for trim case 4 where fuel levels are at 10% and no special forces are embarked. The disparity between the two requirements is best seen in Figure 20. Only a low sweep angle provides a satisfactory margin in the extreme low load case (pink line). This would have the effect of reducing the responsiveness of the aircraft when trimmed. It would also mean that a large nose up trim force would be required from the elevons in order to reach a trimmed state. In this mode, the moment arm between centers of gravity and buoyancy is 7.5 inches which is probably acceptable if control surfaces are used to maintain trim.

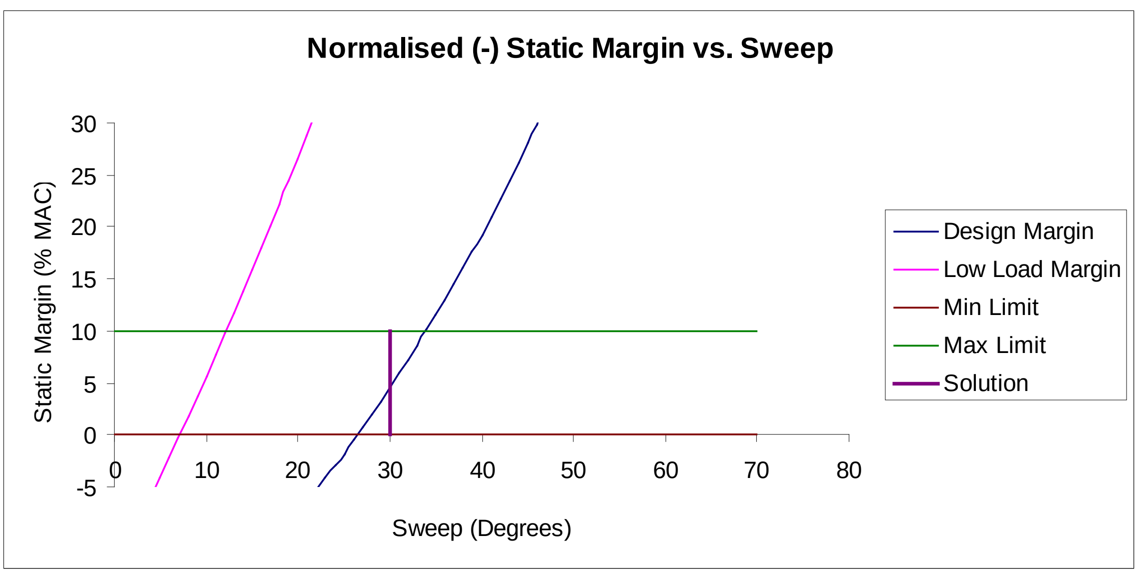


Figure 20: Arrangement 1 design and extreme static margins

A number of options are available to overcome this in-flight stability issue in trim case 4. A change in arrangement in future iterations could place the worst case center of gravity more closely aligned with its ideal position. However, the current arrangement does offer

very good submerged trim and is well suited in all other respects. A more practical approach may be to partially flood the wing ballast tanks or retain seawater within the Special Forces compartment in order to manipulate the center of gravity. A similar effect may be achieved by sealing the compensating water in the fuel tanks as the vehicle surfaces.

8.2 Arrangement 2

Arrangement 2 is seen in Figure 21

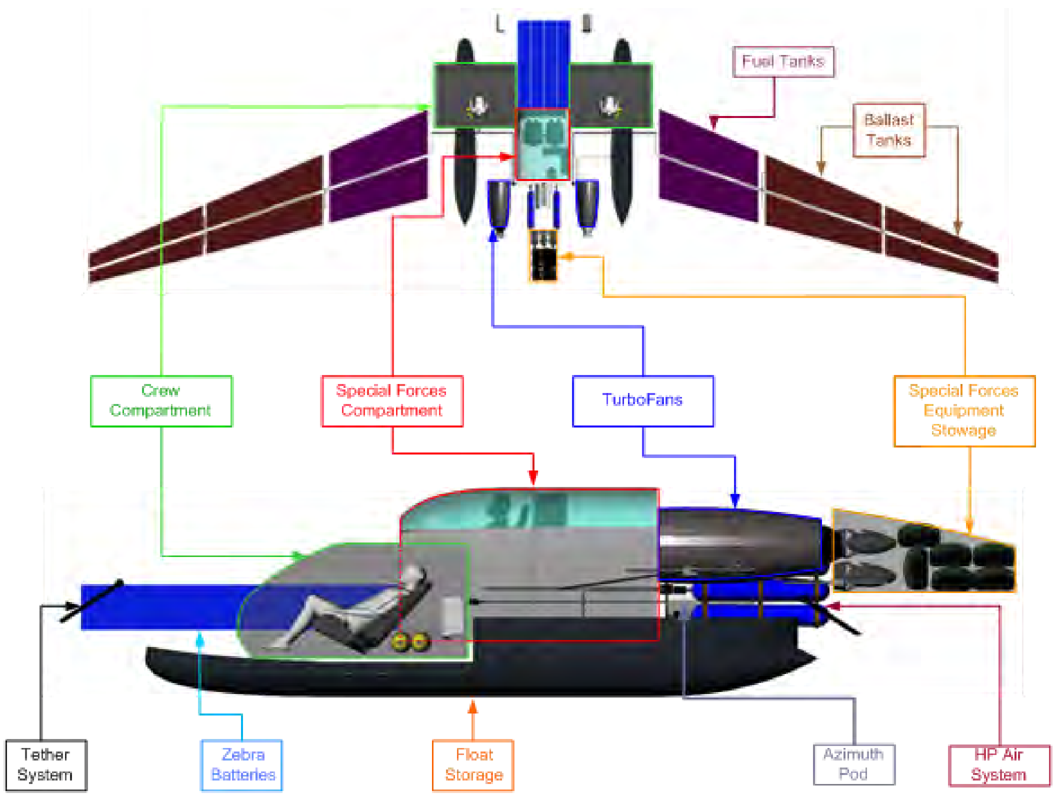


Figure 21: General arrangement – Arrangement 2

Similarities exist with arrangement one. The location of the turbofans is unchanged, being positioned as low to the root chord line as possible and aft to avoid spray. Fuel and ballast tanks remain located within the wing with fuel inboard. Similarly, the inflatable pontoon storage is found in the same location with slight changes longitudinally to place the center of buoyancy of the floats nearer to the center of gravity. The high pressure air system and drop-down azimuthing pod remain located aft of the cockpit.

The most significant difference between the two arrangements lies in the positioning of the Special Forces compartment. Arrangement two splits the six man deployment in two allowing them to be positioned either side of the pressure hull. This also allows the compartments to be positioned more efficiently within the fairing leading to a lower profile centerbody. Seats are reclined to reduce the overall compartment height whilst maintaining head room. Batteries are positioned forward of the cockpit between the two Special Forces compartments with the equipment stowage aft of the drop down azimuthing pod. Special Forces deployment is again through hatches in the top of the compartments set into the upper surface of the fairing.

As with Arrangement 1, all equipment outside the cockpit is subject to free flood conditions. Figure 22 shows wing plan for Arrangement 2 and Table 9 shows the corresponding wing principal particulars.

Principal Particulars	
Weight	38,960 lbs
Wing Span	109 ft
Length	34 ft
Main Wing Sweep	25 degrees
Tip Sweep	-5 degrees
Main Wing Taper Ratio	0.3
Tip Taper Ratio	0.5
Station 1 Airfoil Section	E184
Station 2 Airfoil Section	E184
Station 3 Airfoil Section	E184

Table 9: Arrangement 2 – wing principal particulars

Figure 22: Arrangement 2 wing layout and profile

In this arrangement, a number of main section sweeps provide acceptable static margins in both design and extreme loading conditions as illustrated in Figure 23.

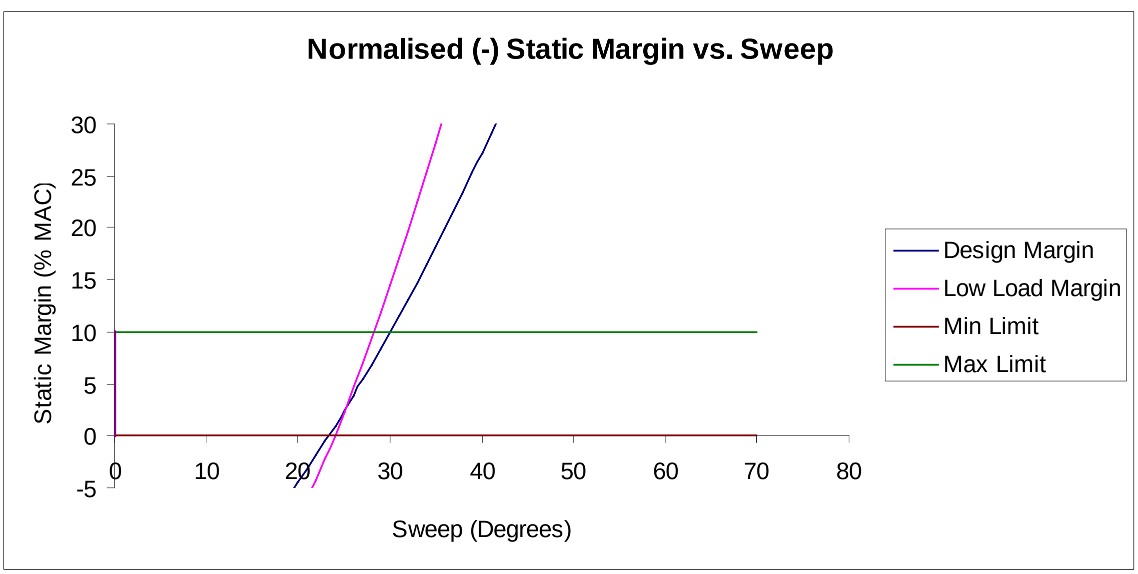


Figure 23: Arrangement 2 design and extreme static margins

A sweep of 25 degrees was chosen to give design and extreme loading margins within the recommended limits (between 0% and 10% mean aerodynamic chord). The main reason for these more limited movements in center of gravity position with loading is due to the close proximity of all variable weights. By positioning the Special Forces and fuel tanks so close to the center of gravity, there is much less sensitivity to change in loading and static margin.

The moment arm between center of gravity and center of buoyancy is 1.6 feet. This is large enough to potentially cause issues with underwater trim. Movement of dense (greater than sea water), non-variable loads such as the battery should allow this value to be effectively reduced as the change in center of gravity will outweigh the change in buoyancy.

Of note is the difference in final weight and wing span between Arrangements 1 and 2. This is mainly due to the added weight of the extra pressure hull housing the Special Forces and the added fairing and width required to house them transversely as oppose to longitudinally. This may be reduced in future iterations by more closely arranging fuel tanks and Special Forces compartments.

9. Scale model design and test

With the methodology in place to design a submersible aircraft concept and two indicative arrangements produced, the validation of some aspects of the design process was achieved through the production of scale models of each of the arrangements. The primary aim of these models was to test the in-air and surfaced maneuverability and operation aspects of the designs. This would allow the optimum position of center of gravity in both air and surfaced modes to be explored. Due to time constraints, only the Arrangement 1 model was complete, finished and tested. The design, build, and test process of this model is presented in the following section.

9.1 Scaling

Because the materials used for the model build were not the same as those envisaged for the full scale craft, it was necessary to scale weight and dimensions independently. Model size was set at a limit dictated by ease of handling and feasibility of operation in an enclosed space. A 6 foot wingspan was selected. It was from this that all other dimensions were calculated. Weight and required thrust were estimated using the cube of the span as the scale factor.

Model wings were constructed from 1.3 lb/ft^3 Expanded Poly-Propylene foam (EPP), a standard aero modeling material. EPP is favored for its impact resistance, durability and resistance to most epoxy resins.

Wings were ordered from a commercial supplier and cut using a computer controlled hot wire cutter to high accuracy. Carbon rods recessed into the underside of the wing provide strength and stiffness in bending. The foam is then further stiffened with longitudinally strengthened strapping tape and protectively coated in ultra-violet resistant tape.

Propulsion is supplied by two 11 V, 46 A brushless motors each supplying a static thrust of 1.7 lbf. This exceeds the expected power requirement but was considered prudent in order to ensure success. Throttle control of the motors is achieved through two 60 A digital speed controllers which connect directly to the radio receiver providing it with power through an incorporated Battery Eliminator Circuit (BEC). The receiver is a 7

channel 2.4 GHz standard *Futaba* receiver which is paired with a commercial model transmitter. This arrangement is seen in Figure 24 mounted on the upper surface of the wing.

Figure 24: Model arrangement of speed controllers, receiver, battery and ducted fans

Port/starboard variable thrust is achieved through channel mixing on the transmitter processor. The motors are housed within ducted fan cowlings giving similar properties to a full scale turbofan. The ducted units are then mounted on the upper surface of the wing using aluminum brackets manufactured in the NSWCCD machine shop which are embedded and epoxied into the EPP foam. The thrust line was set very close to the root chord line of the model with between 1 and 2 degrees of downward angle to counter the nose down tendency expected when the throttle was opened.

Control surfaces were simplified to two elevons extending the full length of the trailing edge. Whilst this was larger than the control surfaces estimated in the full scale design, it was considered necessary to ensure full control authority over the model, particularly at low speed. Each flap is controlled by a standard *Futaba* servo-motor connected directly to the receiver. Elevon functionality is achieved through channel mixing within the transmitter. Elevon arrangement is seen in Figure 25 showing the servo mounting and control surface linkage.

Figure 25: Model elevon arrangement showing servo mounting and linkage

Power is supplied to the speed controllers through a 4 cell 3300 mAh 14.8 V lithium polymer battery pack. Fully charged, this gives approximately 5 to 10 minutes of powered flight before being recharged using a combination charger and balancer ensuring even load on all component cells.

Scale floats were hand carved by the model shop at NSWCCD from scaled 3-D CAD designs, manufactured from high density Styrofoam, and coated with several layers of fit for purpose varnish. This approach resulted in a set of strong lightweight floats. Planing performance is very sensitive to longitudinal position. Float attachment to the underside of the wing was achieved using high strength Velcro™ to allow adjustments while testing.

9.2 Testing

9.3.1 Glide test and center of gravity calibration

Location of the battery pack was left unfixed so as to allow calibration of the model through a series of glide tests.

Gliding tests were conducted using the Arrangement 1 model prior to installing the propulsion battery. In order to achieve stable trimmed gliding flight, it was found that the center of gravity was a few inches further forward than predicted

resulting in a larger static margin. Likely causes for this discrepancy lie in potential inaccuracies in the estimation of center of lift which was calculated numerically.

Favorable gliding flights were achieved with this configuration, albeit with the design being below scale weight.

9.3.2 Powered flight

All powered flight testing took place at a local model airfield which offered a large uninterrupted flight space. Initial tests were carried out to ensure the model was correctly trimmed with the motor installed before the first full flight was conducted.

The initial powered flight was hand launched without floats installed. Despite some initial pitch perturbations, a number of comfortably controlled circuits were accomplished before landing smoothly. During this initial flight, the remaining nose down moment as a result of the throttle activity, and possibly the larger static margin, was trimmed out with small corrections using the servo trim facility on the controller. Before a second flight, the throw length of the servo arms was slightly increased to give a little more range in the elevons deflection. This improved longitudinal trim. Take-off was achieved from the ground within a distance of around 15 feet despite the friction of the wing on the grass surface. Of interest was the excellent directional control on the ground, most probably due to the location of the elevons in the backwash from the motors.

The test day was clear but gusty with wind speeds reaching approximately 10-15 knots. Despite this, flight characteristics were stable. Of particular note was the aircrafts yaw control which was anticipated to be a potential issue in the absence of a vertical stabilizer. Despite the strong cross-winds, the aircraft displayed only slight crabbing and very good directional stability. Control authority through the elevons was sufficient despite weather conditions and smooth turns were easily achievable.

During this test there was only one uncontrolled descent. This occurred during a highly banked tight turn away from a head wind. A strong gust caught the exposed underside of the wing, causing it to flip. Due to the low altitude at the time, recovery was not possible. However, no damage was incurred. This was not believed to be a significant problem as the scale velocity of the wind was high and no maneuvering limitations were imposed to restrict the aircraft to more gentle turns and lower bank angles.

The effect of variable thrust between port and starboard engines was next investigated. Use of variable thrust between port and starboard engines for yaw control proved to be very effective particularly at low speed. It was described as being comparable to having a very efficient rudder installed. The advantage of this system, as opposed to a traditional rudder, lies in the reduction in drag. A vertical stabilizer would produce induced, interference, frictional and form drag components while a variable thrust system adds no additional drag to the aircraft. This is particularly important when submerged where the drag forces are several orders of magnitude larger than in air and steering forces are provided by the azimuthing pod.

Attempts were made to fly with floats installed to investigate the effect this would have on the trim and control of the aircraft. Although a number of attempts were made, directional control was impossible to achieve as the vehicle had a tendency to yaw and roll severely at all speeds. This is attributed to the method used to attach the floats to the wing. Velcro™ was used to allow flexibility in longitudinal location which resulted in an amount of lateral flex. Any inaccuracy in alignment of the floats initiated a yaw moment on the aircraft. As the aircraft began to turn, the slab walls of the floats acted as an unfixed rudder, exacerbating the control problem. The resulting loss of control in the tests resulted in some damage to the model and ended the testing session. Use of a rigid attachment may alleviate / eliminate the problem.

9.3.3 Surface maneuvering

Use of the NSWCCD Maneuvering and Seakeeping facility (MASK) was secured for an afternoon to carry out surface control tests. The aim of these tests was to ascertain the optimum longitudinal placement of the floats relative to the aircraft center of gravity and center of lift, the planing characteristics of the vehicle, spray patterns and the effectiveness of variable thrust as a means of surfaced directional control.

Initial float tests were carried out to find a longitudinal position that gave an acceptable stationary trim before beginning powered trials. The aircraft was seen to float slightly below the design waterline but was still below the turn of bow in trimmed condition.

A series of taxiing maneuvers showed that the spray from the inboard side of each float was entering the intakes of the ducted fan as speed increased. Floats were next positioned 20 mm further forward, trimming the vessel down by the stern and reducing the clearance of the trailing edge from the water. Further taxiing maneuvers were performed. The direction of spray was greatly improved with outboard spray directed over the leading edge and inboard spray deflecting off the underside of the central fairing. Figure 26 shows this spray pattern prior to the model reaching planing speed.

Figure 26: Spray generation before planing condition

Concerns that the trailing edge may interact with the water were unfounded as the moment from the thrust combined with the trim of the hulls as they accelerated

lifted the trailing edge comfortably clear. Figure 27 shows this trailing edge clearance as well as the large quantity of spray deflecting from the underside of the wing and exiting aft.

Figure 27: Model trials showing trailing edge clearance and spray levels

Confident that spray intake was no longer an issue, thrust was increased to determine whether a planing state was achievable. Because the model was trimmed aft quite significantly, it very quickly began to climb its bow wave even at relatively low speeds. Observation suggested it reached the peak of the planing 'hump' at around mid-throttle (equating to approximately 1.5-1.7 lbf of thrust) and reached full planing conditions with very little extra thrust (noted visually by an abrupt change in trim). Scale installed power is predicted at approximately 2.1 lbf which corresponds well to what was seen on the water. Figure 28 shows the model transition onto the plane. Large amounts of spray emanating from the outboard bow chine are evident in still 1. The spray sheet moves aft and reduces as the vehicle accelerates. Still 7 shows the vehicle fully planing at an acceptable trim. Stills 8 and 9 show short flight hops as the model encounters its own wake.

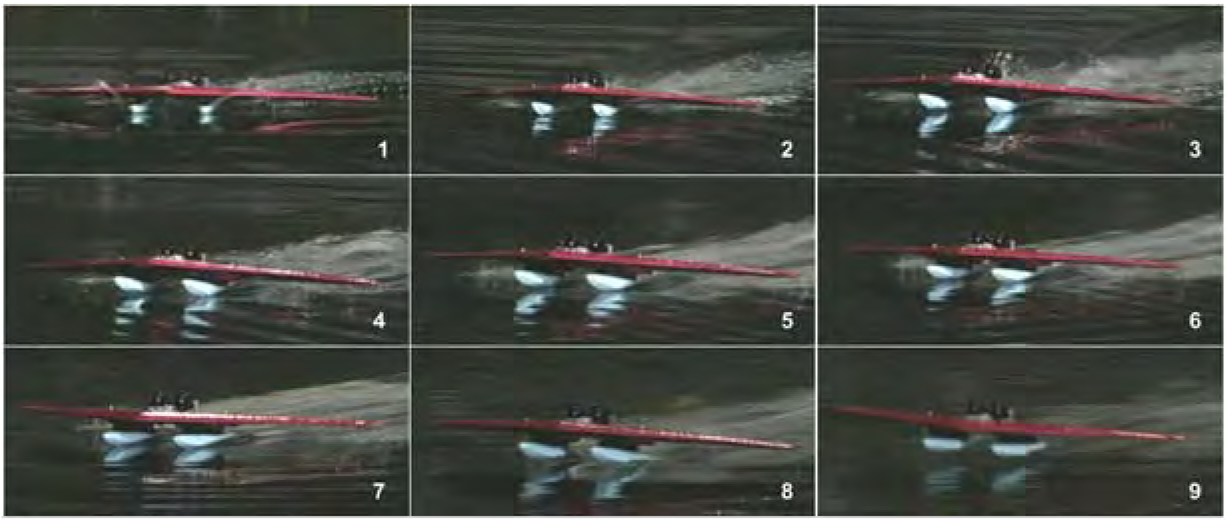


Figure 28: Scale model planing transition (stills from video)

Attempts made to reach take-off speed and carry out a short take-off and landing were unsuccessful due to difficulty in maintaining directional control, particularly as speed increased. This was attributed to inaccuracies in aligning the floats and the inherent flex still present in the Velcro™ float attachment. Future attempts with a more permanent fastening method are expected to be successful.

9.3.4 Scale test conclusions

The scale model tests conducted validate aspects of the concept design of the submersible aircraft. The successful flight tests proved that the method used to arrive at a stable tailless wing configuration was valid, producing a design with excellent directional stability, particularly in yaw. Control was adequately provided with single flap elevons. Although this questions the need for split flaps in a final design, split flaps would offer the added advantage of doubling as air breaks. Variable thrust further improved flight handling characteristics, completely replacing a vertical stabilizer without the inherent drag penalties. Some tendencies to approach stall suddenly at low speed were observed but were controllable. Cruise thrust was seen as low as 20-30% of installed power.

Water testing highlighted the sensitivity of performance to longitudinal float placement and, more specifically, longitudinal center of planing lift. To avoid burying the bows, a significant aft trim was required. This is mainly due to the slightly higher waterline than intended. Future float designs should improve on this. As float design is not optimized, spray was initially seen to foul the installed motors. However, once the floats optimum longitudinal position was determined, inboard spray was deflected from the underside of the wing and outboard spray was directed down the swept leading edge.

The effectiveness of the large installed steps on the underside of the floats was impossible to quantifiably analyze. However, a planing state was reached at around 75% of scale throttle and take-off speed reached quickly afterwards. Whether the steps ventilated successfully and contributed to lowering the drag is unknown. More controlled tow tank testing is recommended. Future float design should improve spray characteristics and reduce planing speed since the significant aft trim needed probably increased the thrust required to overcome the bow wave, whilst resistance due to spray was probably also significant.

Maneuverability on the surface was easily achieved through variable thrust with the model comfortably being able to turn within its own length if required. Maneuvering under elevons alone was not attempted.

Take-off should be feasible with the floats more rigidly attached. Further tests should be carried out to examine the flight characteristics of the design with floats attached. It is widely reported by float plane pilots that take-off is achieved more easily with lower power requirements in head wind conditions with a sea state. Tests in the MASK demonstrated take-off power was sufficient with neither of these factors present. Of some concern is the effect of waves on the design. Careful design will be needed of the float attachments and floats themselves to ensure that sufficient clearance is present between wing tips and water surface. Trailing edge interaction with the water is not considered to be an issue as careful float design should present a more statically trimmed vehicle.

10. Further work

During the submersible aircraft study, the main aspects of the design have undergone a detailed assessment. In order to enhance the design, further areas of work should be considered such as:

- optimizing the inflatable float design looking into alternative hull forms and configurations.
- carrying out a structural study on the design of the floats, focusing on the effects of the proposed air beam technology/drop-stitching.
- undertaking a detailed study into the watertight sealing of the airborne propulsion system.
- undertaking a detailed study into the control surfaces for all three modes of operation.
- conducting further optimization of the wing design process, utilizing the outputs computed within Tornado to further improve the final configuration. This should include the impact of high lift devices and their durability to submergence.
- a more detailed structural analysis including the effects associated with wing loading to refine and optimize the structural design.
- looking into the effect of using advanced materials during construction.
- performing an integration study into current naval assets for an at-sea deployment solution.

Further development of this submersible aircraft concept will provide significant benefits to the design of submersible aircraft in general as well as build upon the solid foundation of this concept. The current interest from both the US Navy and DARPA to develop a platform that fulfills the highlighted capability gap further enhances the desirability of undertaking the recommended research topics outlined above.

11. Conclusions

General conclusions:

- a submersible aircraft concept has the potential to offer a unique force insertion capability to the US military;
- an ideal vehicle for this concept should aim to combine the stealth characteristics of a submersible with the speed of an aircraft and the endurance of a surface vehicle.

Based on the initial design exercise described in this report, the following specific conclusions were drawn:

- feasible vehicle concepts can be generated using current technology and materials;
- a hybrid flying wing/blended body design offers a viable solution, and offers a practical compromise between performance in flight, on the surface and when submerged;
- a critical factor in design is the optimization of center of gravity in relation to the centers of lift while submerged, on the surface and airborne. Its appropriate positioning to ensure trim and stability in each operating mode is a task best undertaken in the early concept stage. Careful design should be able to eliminate or reduce the requirement for a complex control system;
- model flight tests have demonstrated the flying capability of one of the wing designs and the validity of the tools developed to generate them;
- the employment of inflatable floats to fulfill demanding landing and take-off requirements is an efficient way of reducing the volume of the un-deployed system. Engineering development of the concept is required to assure feasibility. Although other more optimal solutions may exist to reduce drag at take-off, any chosen system must minimize volume and parasitic drag when submerged.

12. Acknowledgements

The authors of this report gratefully acknowledge the technical contributions and support of the members of CISD, specifically; Colen Kennell (Technical Director), Jack Offutt (Specialist Contractor) and Andy Tate (UK Exchange Officer) for their encouragement, help and patience.

The efforts of Norman Orlowsky (German Exchange Officer) are particularly appreciated, especially his experience and skill in leading the build of the scale model and his considerable abilities as a test pilot.

13. Contacts

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14. Appendix A – Turbofan & turbo-jet basis data

Engine Model	Max Thrust [lb]	Specific Fuel Consumption [lb.fuel/hr/lbf]	Engine Weight [lb]
RR BR710	14,750	0.39	3,600
RR AE3007H	9,500	0.43	1,644
RR Williams FJ44	1,900	0.46	447

Avco Lycoming ALF502R-5	6,790	0.41	1,336
Garrette TFE731-20	3,500	0.44	885
GE Honda HF120	2,000	0.70	400

Table 10: Basis Turbofan data[23]

Turbofan Fuel Break down				
Specific fuel comsumption (SFC) - max. take off rating			0.42409	lb/hr/lbf
Thrust at Take Off			7400	lbf
Specific fuel comsumption (SFC) - max. continuous rating			0.450665	lb/hr/lbf
Thrust at Cruise			6475	lbf
Specific fuel comsumption (SFC) - idle rating			0.50603	lb/hr/lbf
Thrust at Idle Rating			1850	lbf
Segment	Time hr	Fuel lb		
Taxi in-out	0.17	156.03		
Takeoff	0.03	104.61		
Climb	0.33	972.69		
Cruise	3.73	10894.08		
Descent	0.50	468.08		
Land	0.03	31.21	Fuel with 10%	
Sum:	4.80	12626.69 lb	13889.35 lb	

Figure 29: Example of turbofan fuel calculations from spreadsheet

ngine Model	Max Thrust [shp]	SFC [lb/shp hr]	Engine Weight [lb]
PW127F	2,750	0.459	1,060
PT6A-42	850	0.601	403
GE M601	724	0.585	350
RR500	500	0.62	250

RR M250	450	0.613	212
Garrett TPE331	575	0.591	336
RR AE 2100	4,152	0.46	1,641

Table 11: Basis turbo-prop data

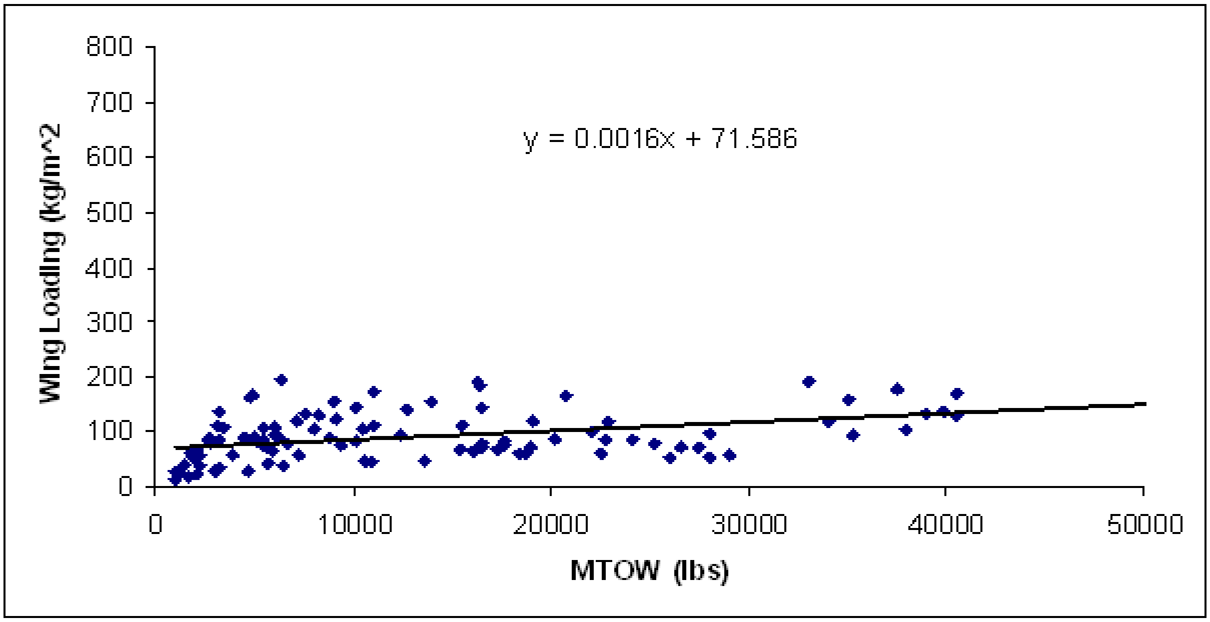
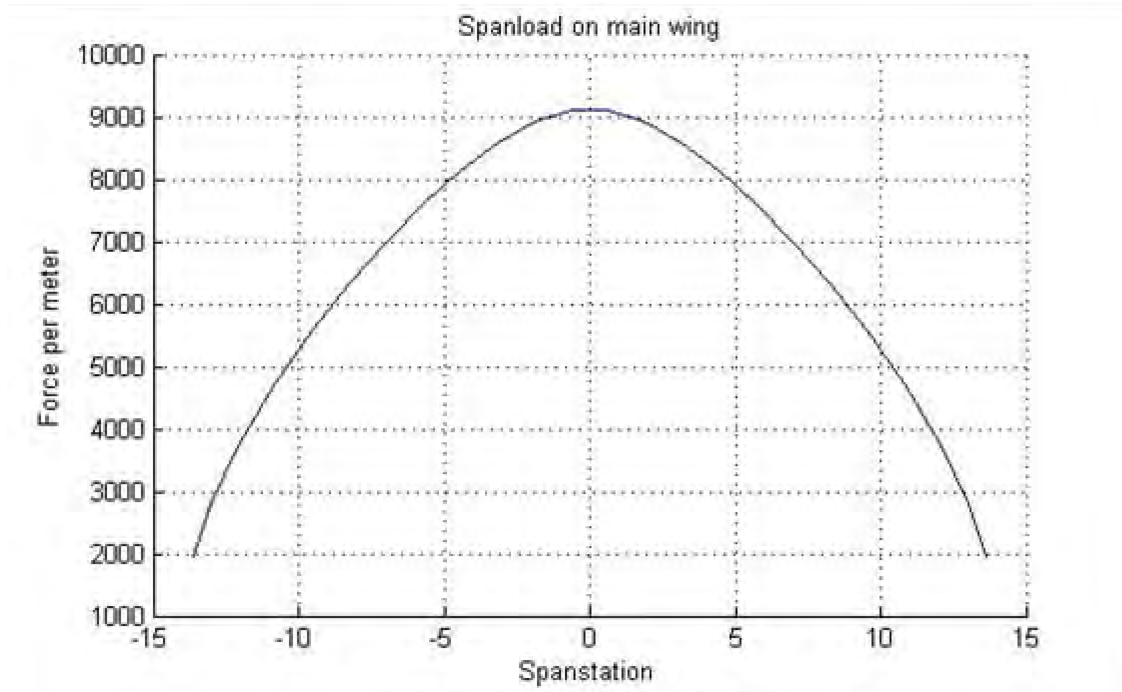
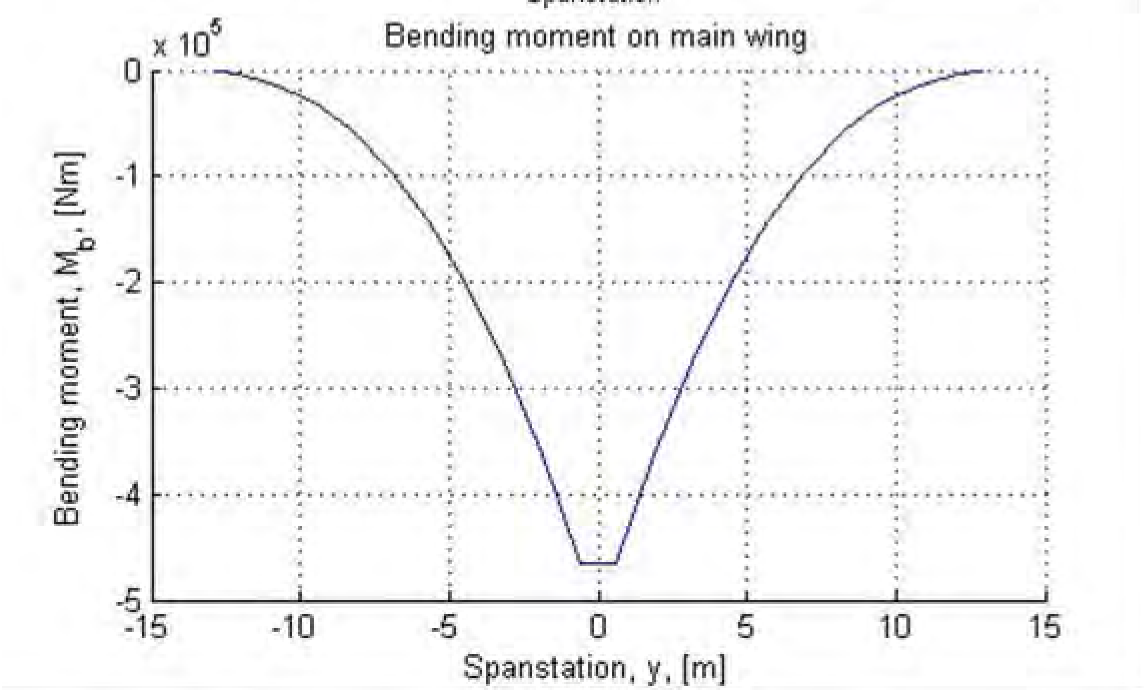


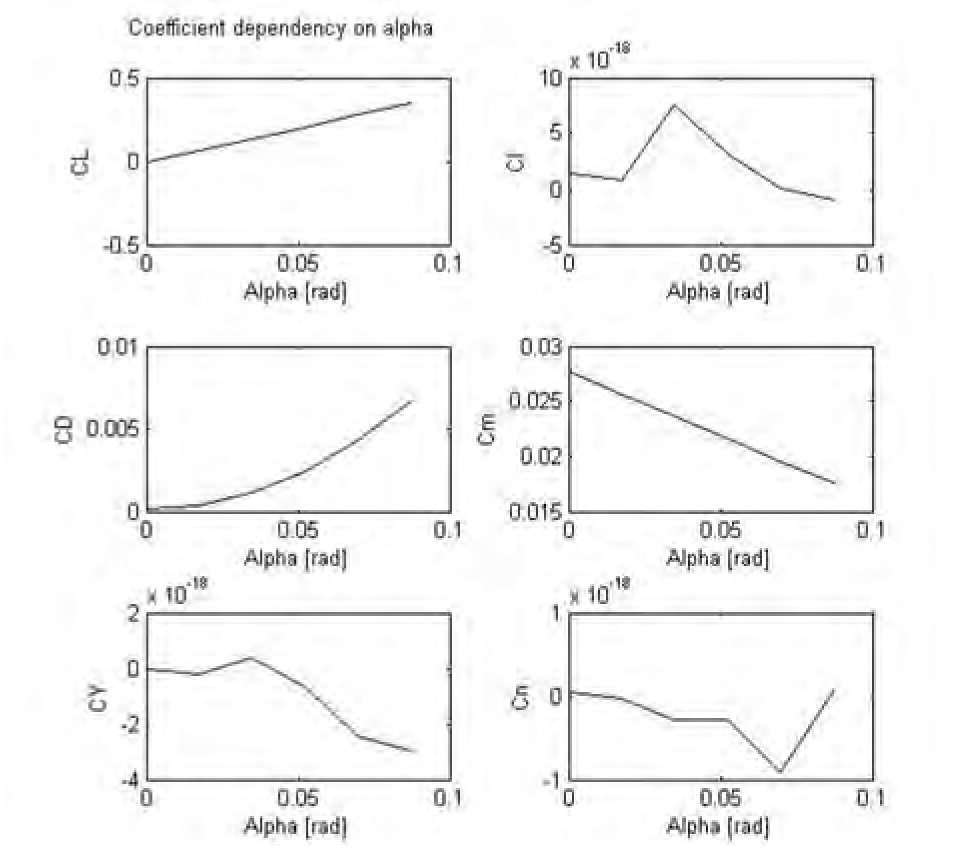
Figure 30: Wing loading

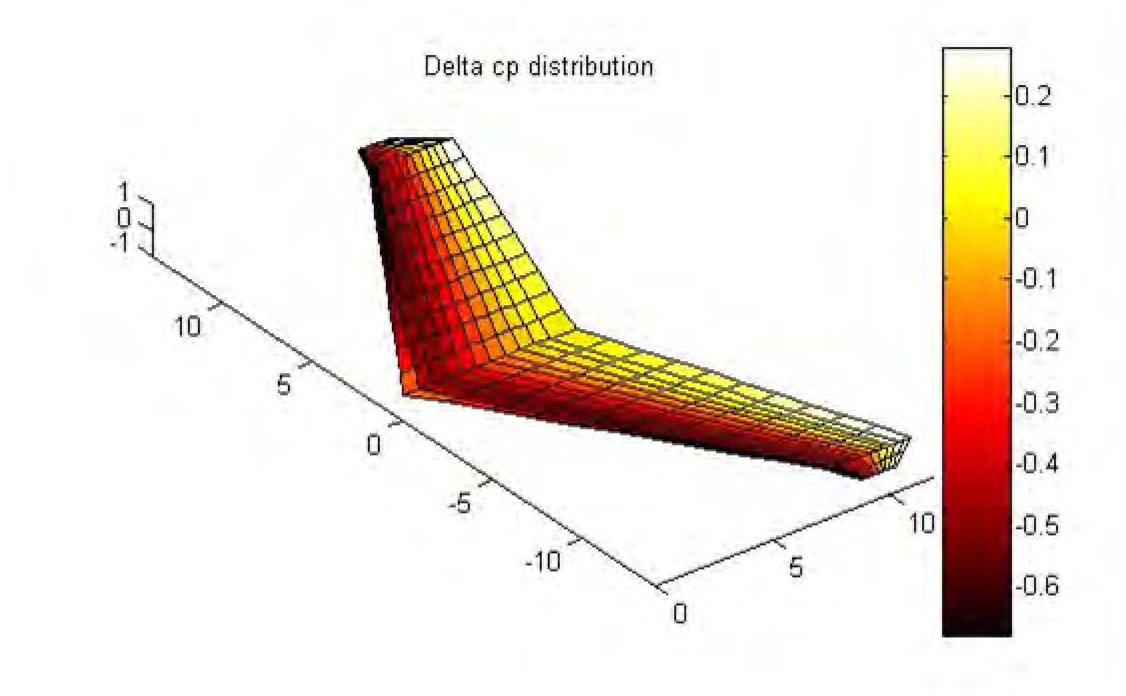
15. Appendix B – Tornado analysis output

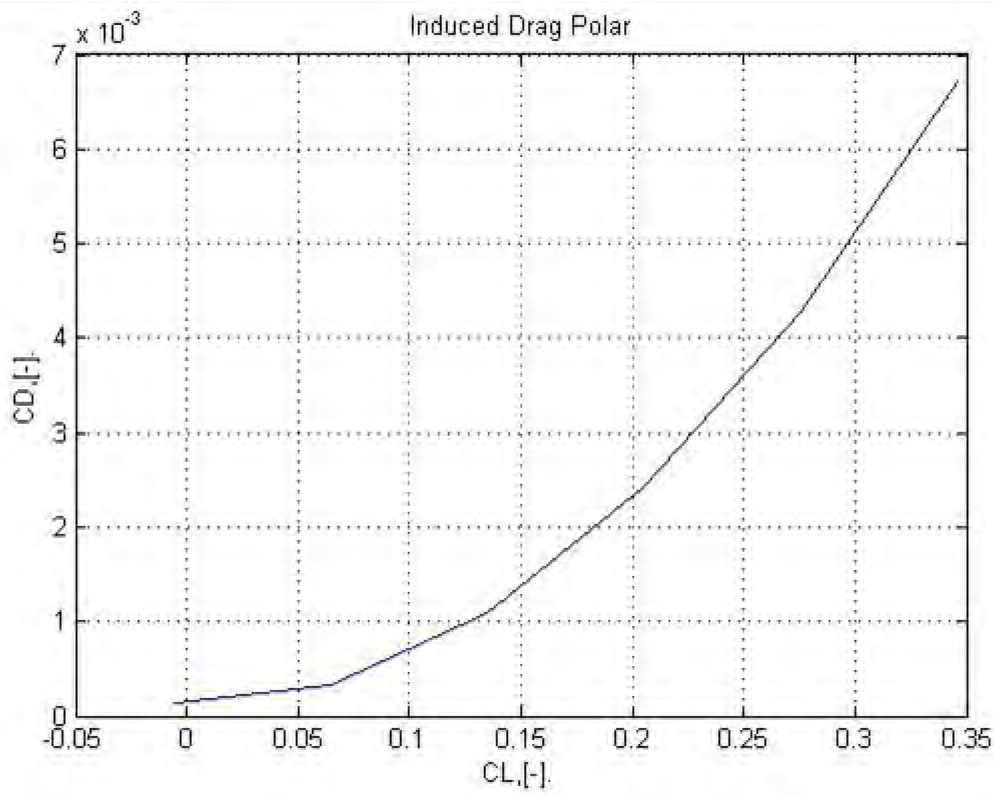
15.1 Tornado output - Arrangement 1

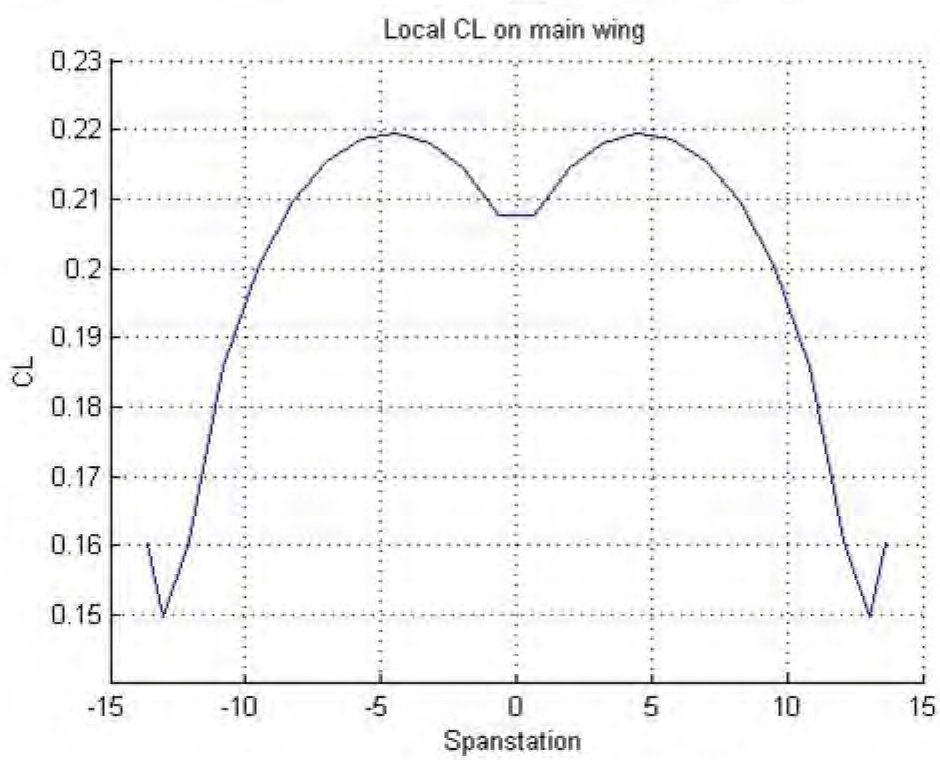


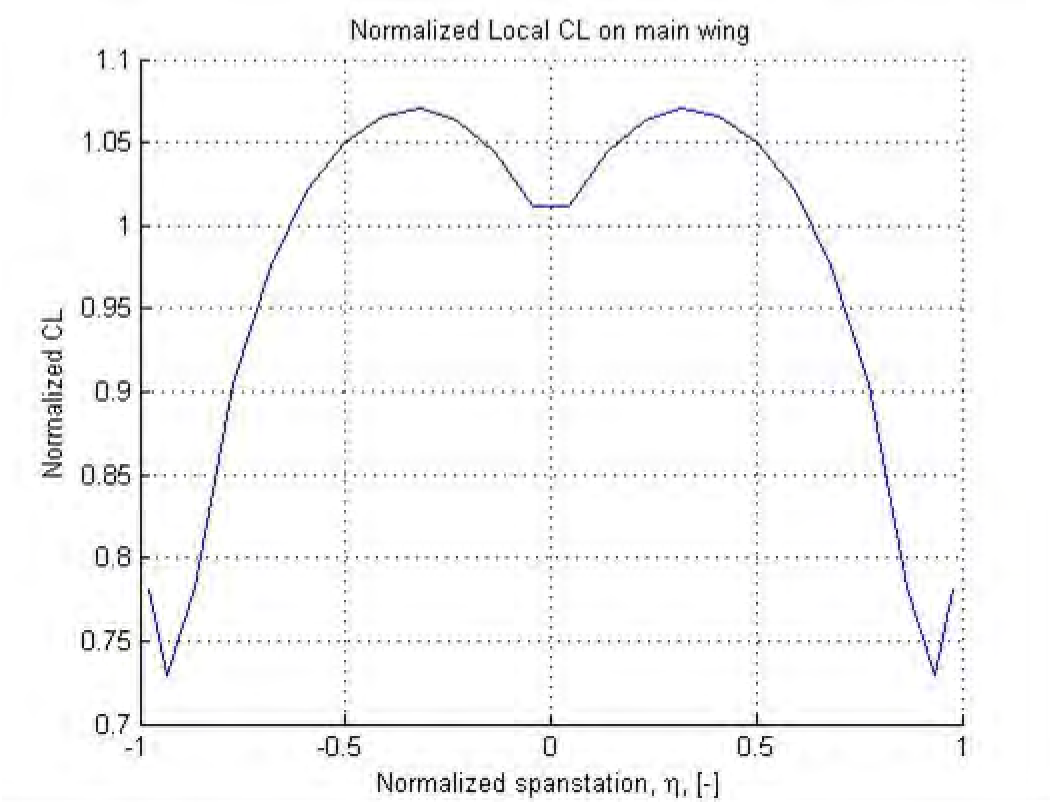


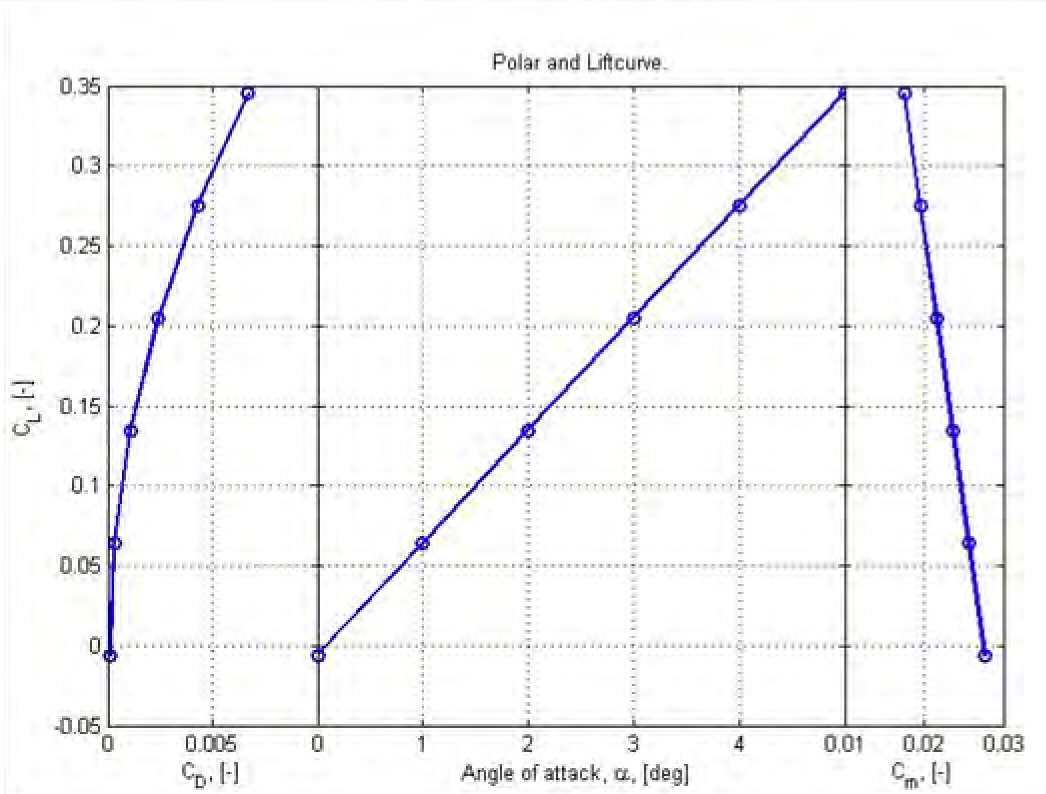

Coefficient dependency on alpha
CL
Cl
CD
Cm
CY
Cn
Alpha [rad]
x 10^-18

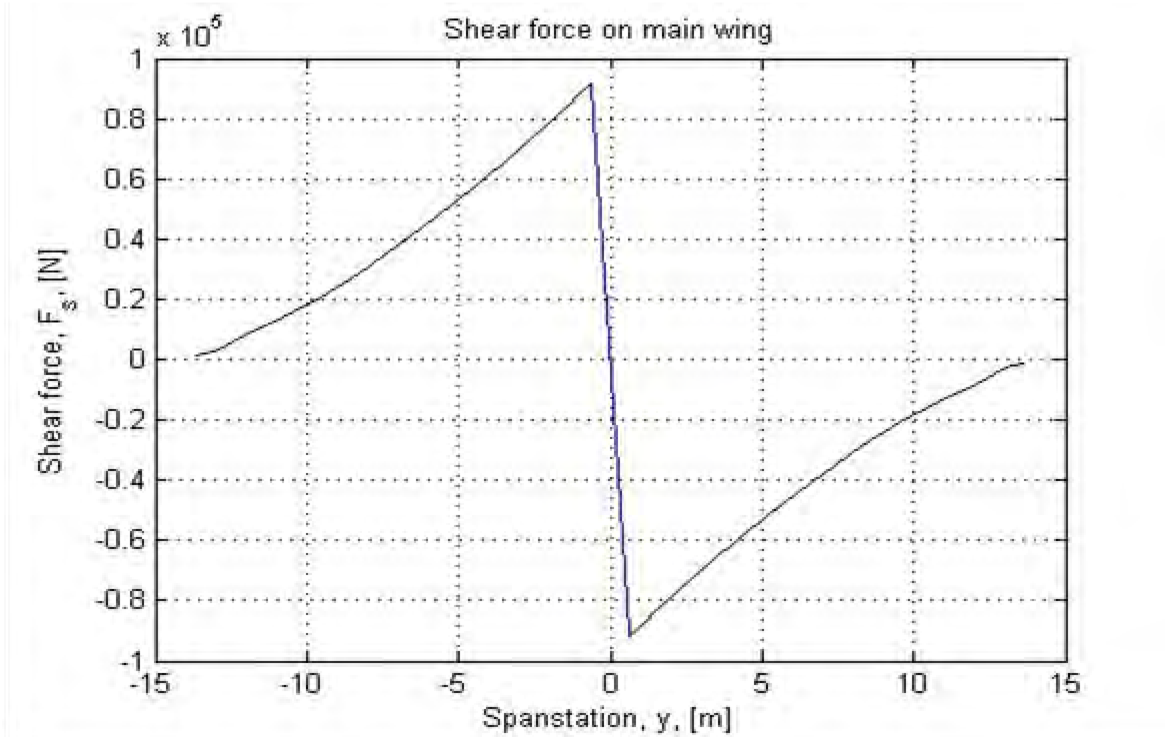

Delta cp distribution


Induced Drag Polar
x 10^-3
7
6
5
4
3
2
1
0
CD,[-]
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
CL,[-]


Local CL on main wing
0.23
0.22
0.21
0.2
0.19
0.18
0.17
0.16
0.15
CL
-15
-10
-5
0
5
10
15
Spanstation


Normalized Local CL on main wing
Normalized CL
Normalized spanstation, η, [-]


Polar and Liftcurve.
C_L, [-]
C_D, [-]
Angle of attack, α, [deg]
C_m, [-]


Shear force on main wing
x 10^5
Shear force, F_s', [N]
Spanstation, y, [m]
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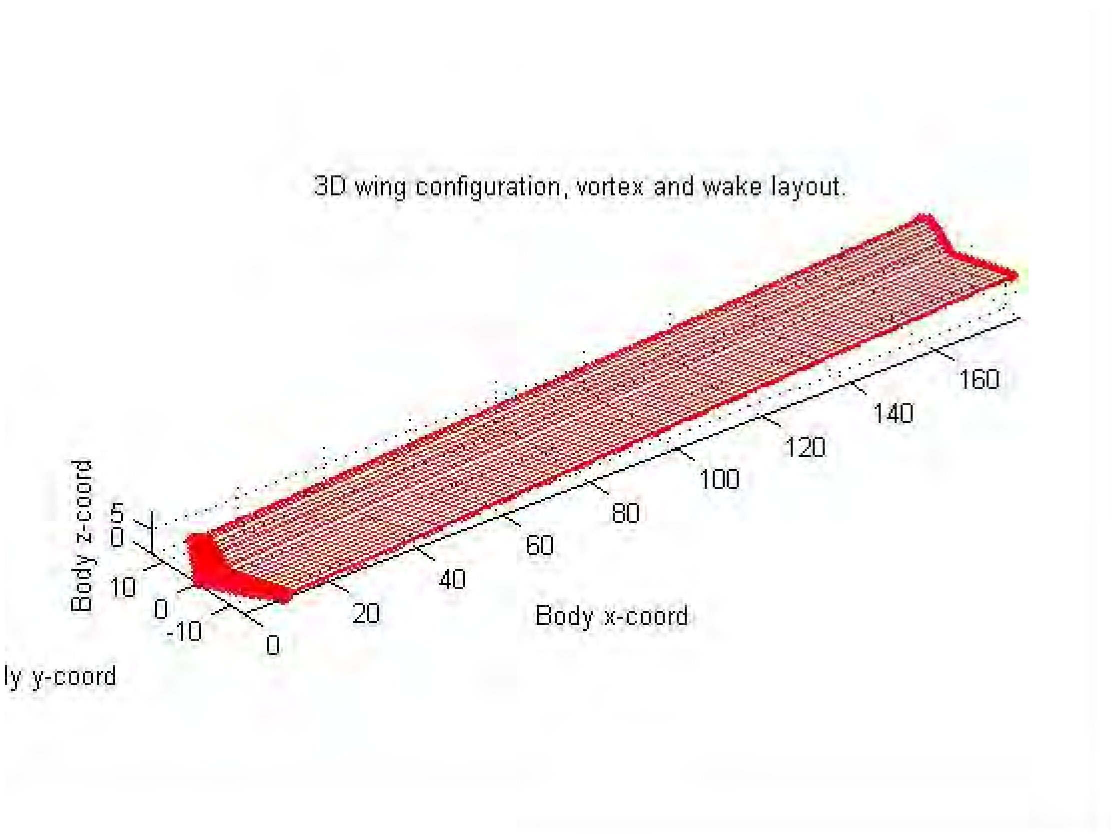
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-15
-10
-5
0
5
10
15


3D wing configuration, vortex and wake layout.
Body z-coord
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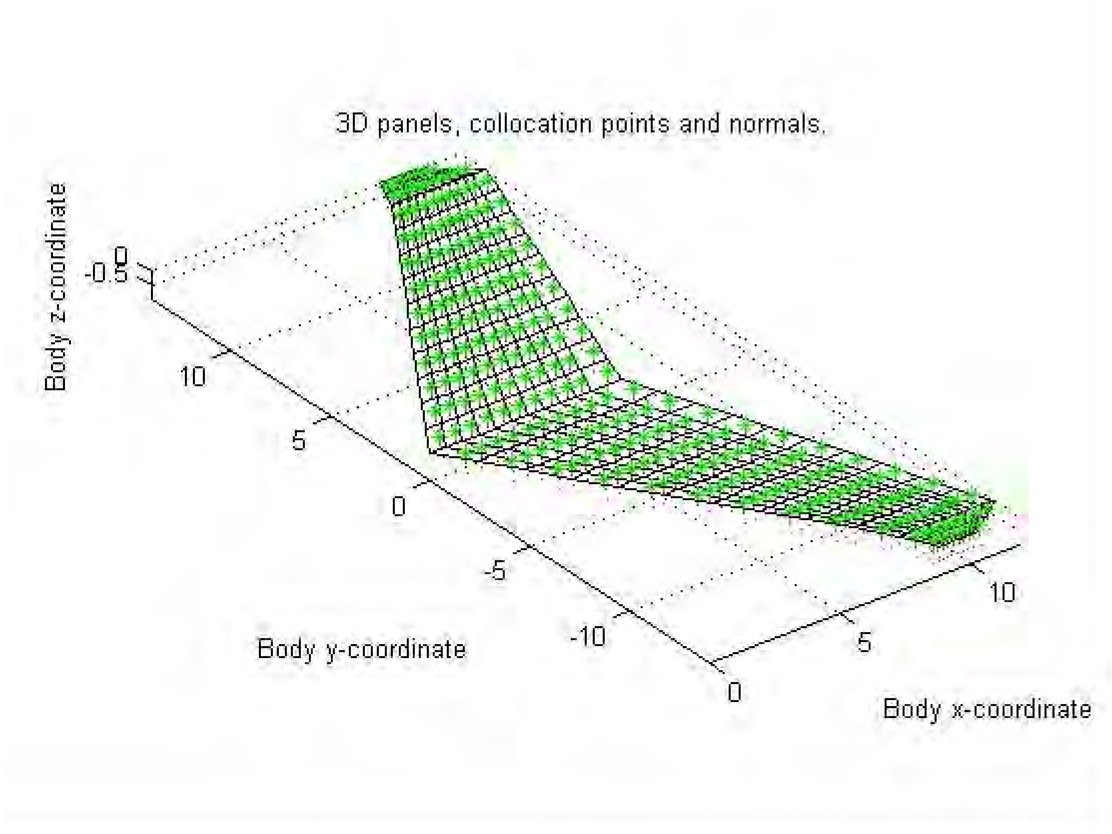
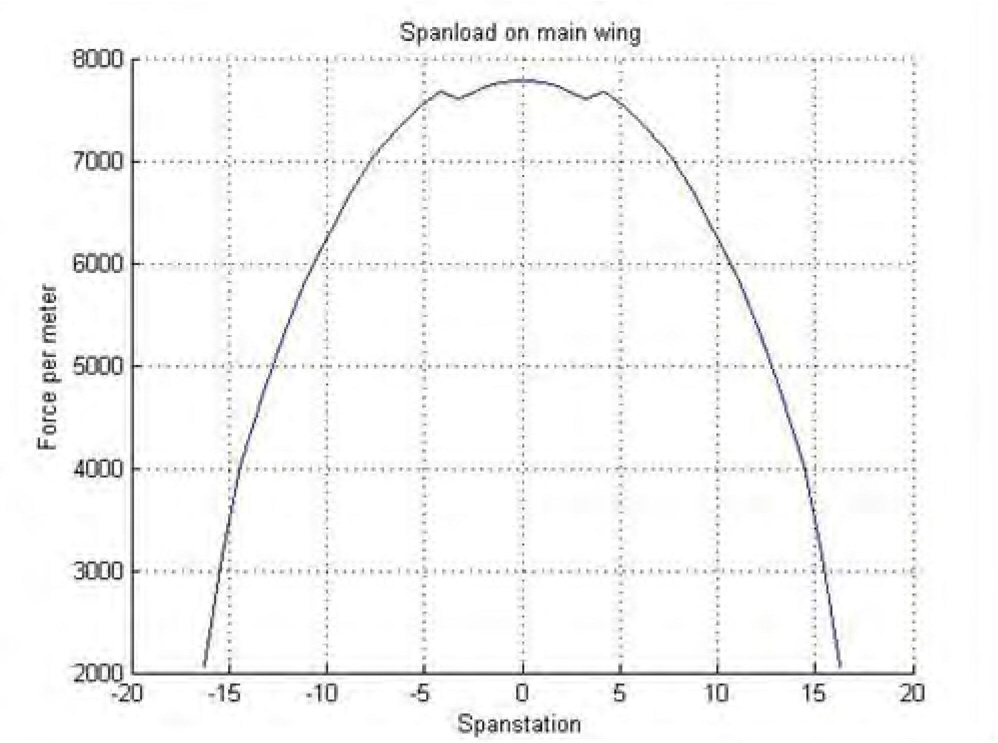
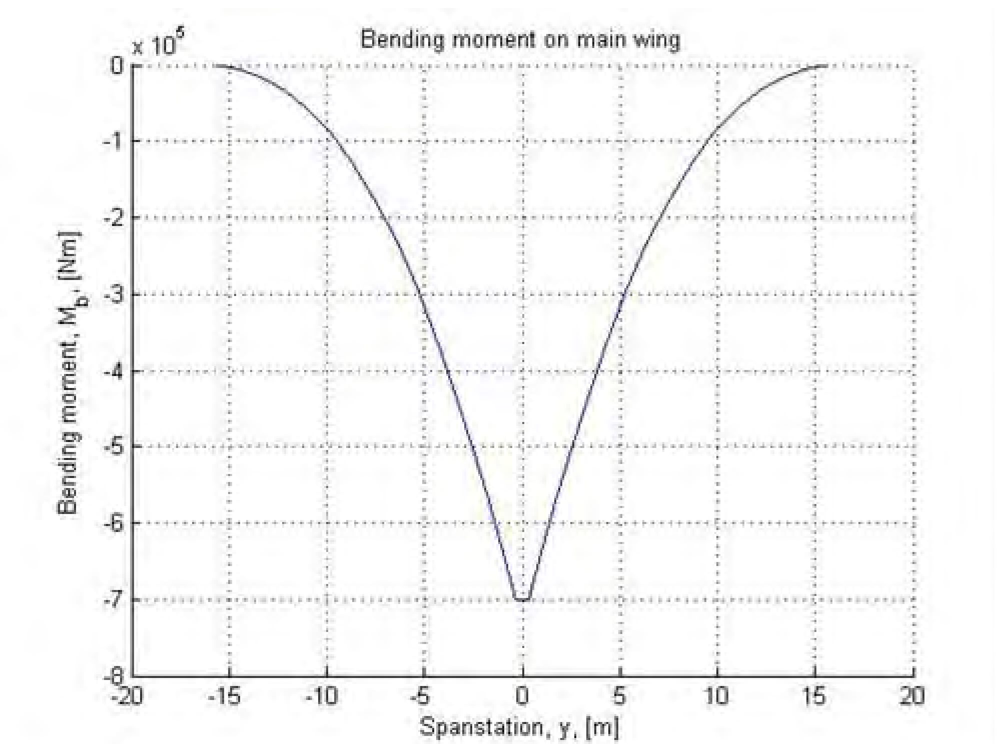
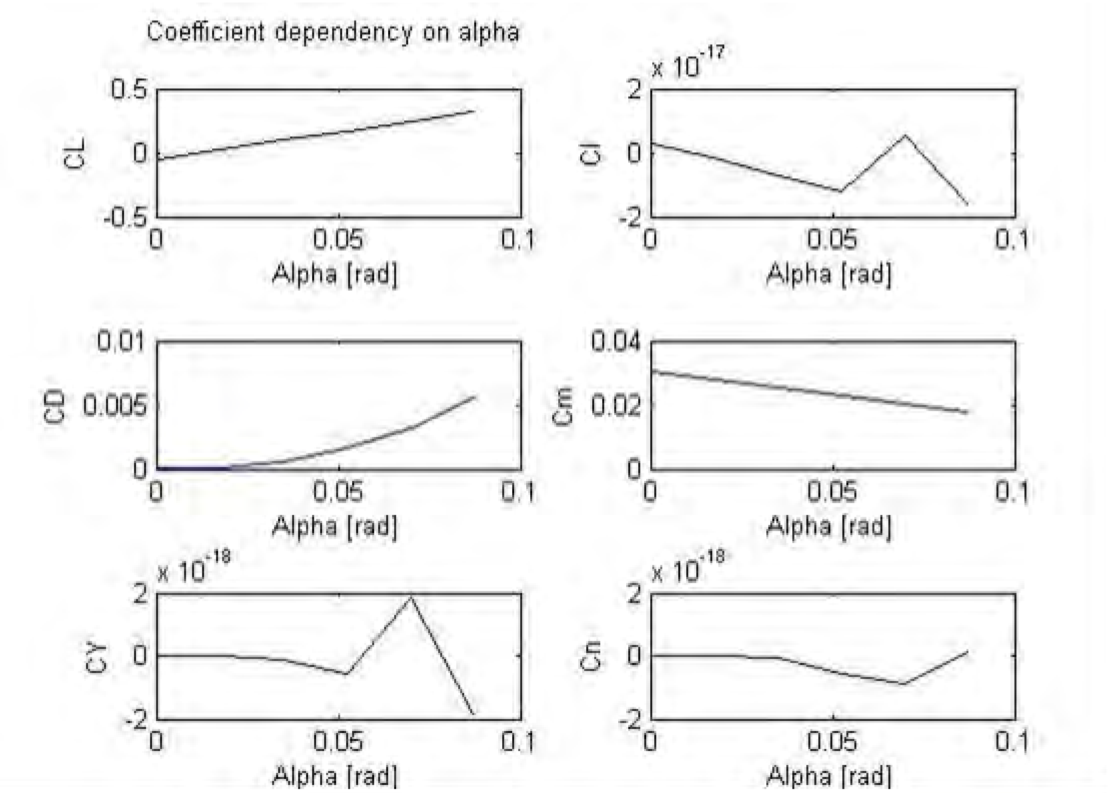
0
10
0
-10
0
ly y-coord
20
40
60
80
100
120
140
160
Body x-coord

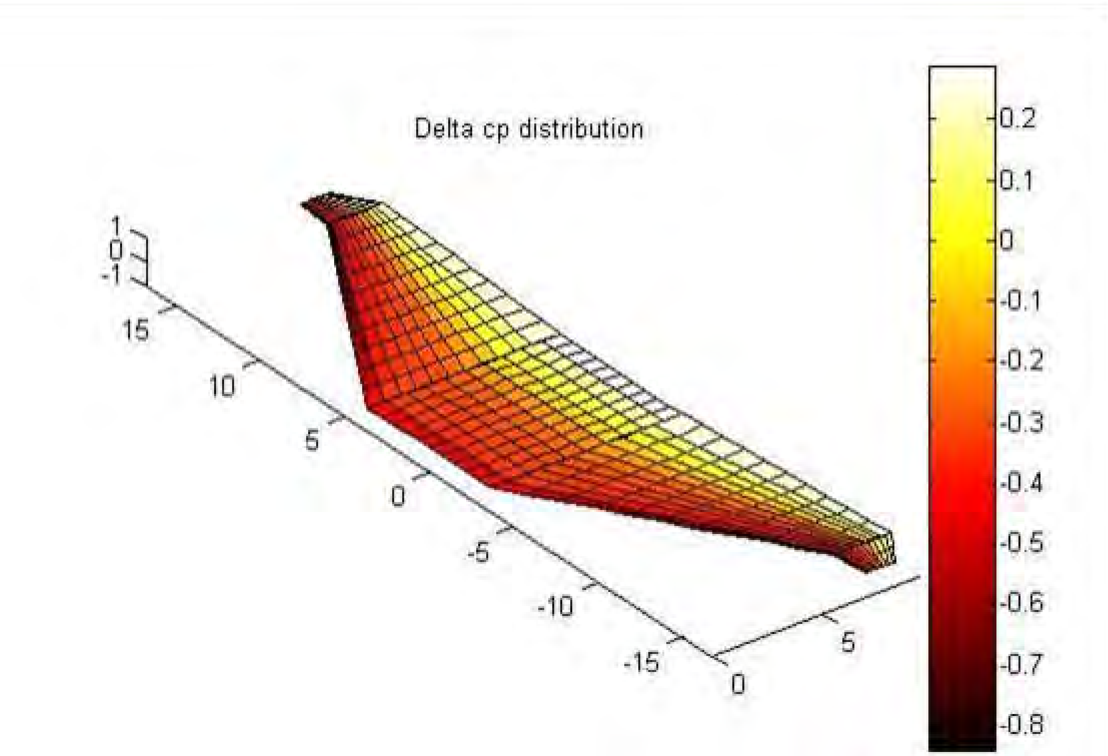

3D panels, collocation points and normals.
Body z-coordinate
0
-0.5
10
5
0
-5
-10
Body y-coordinate
0
5
10
Body x-coordinate

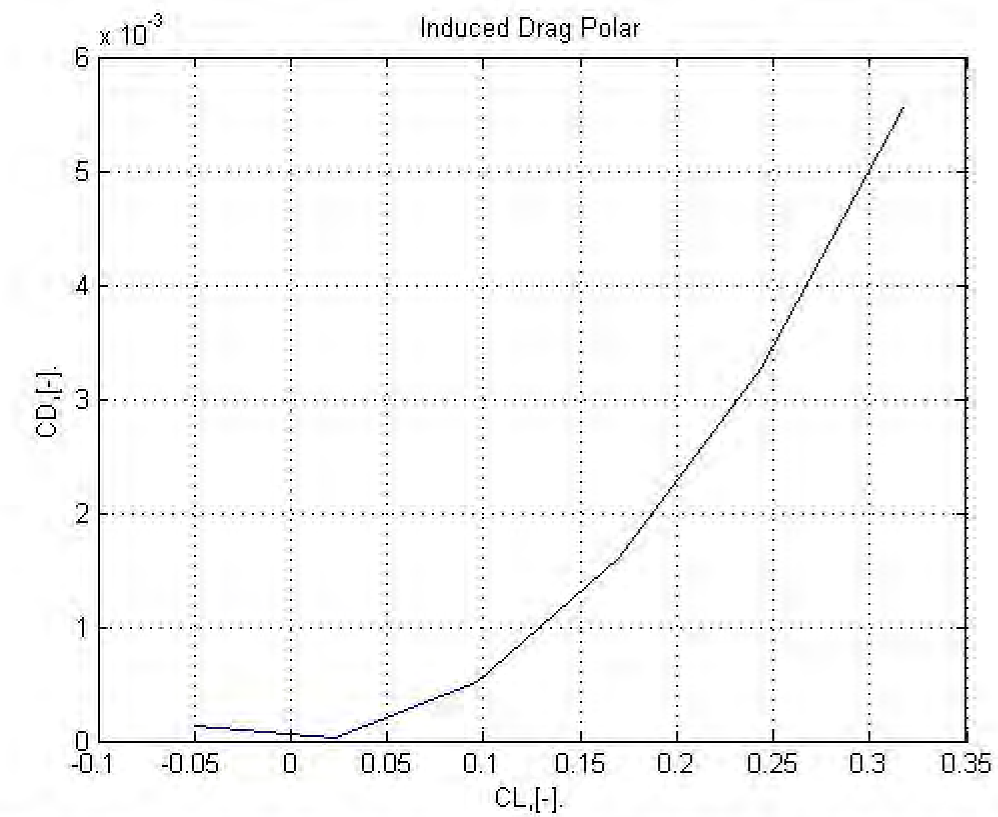
15.2 Tornado output - Arrangement 2






Coefficient dependency on alpha
CL
Cl
CD
Cm
CY
Cn
Alpha [rad]
x 10^-17
x 10^-18


Delta cp distribution


Induced Drag Polar
x 10^-3
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5
4
3
2
1
0
CD,[-].
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0
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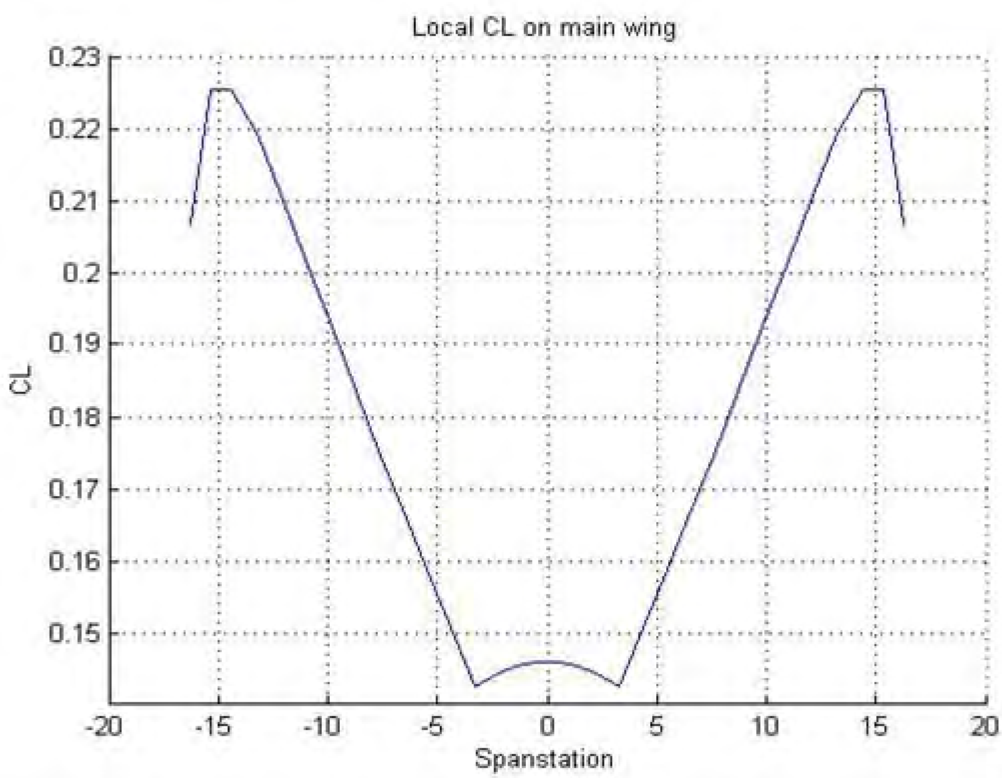
0.15
0.2
0.25
0.3
0.35
CL,[-].


Local CL on main wing
0.23
0.22
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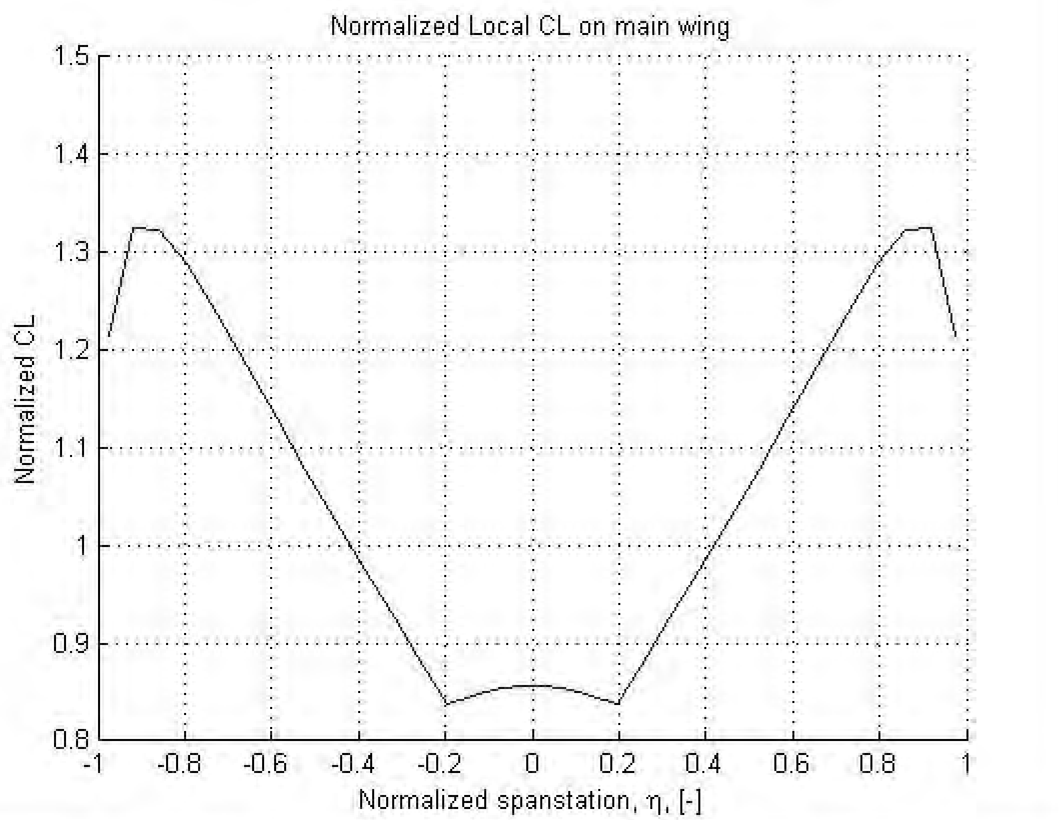
-10
-5
0
5
10
15
20
Spanstation


Normalized Local CL on main wing
Normalized CL
Normalized spanstation, η, [-]
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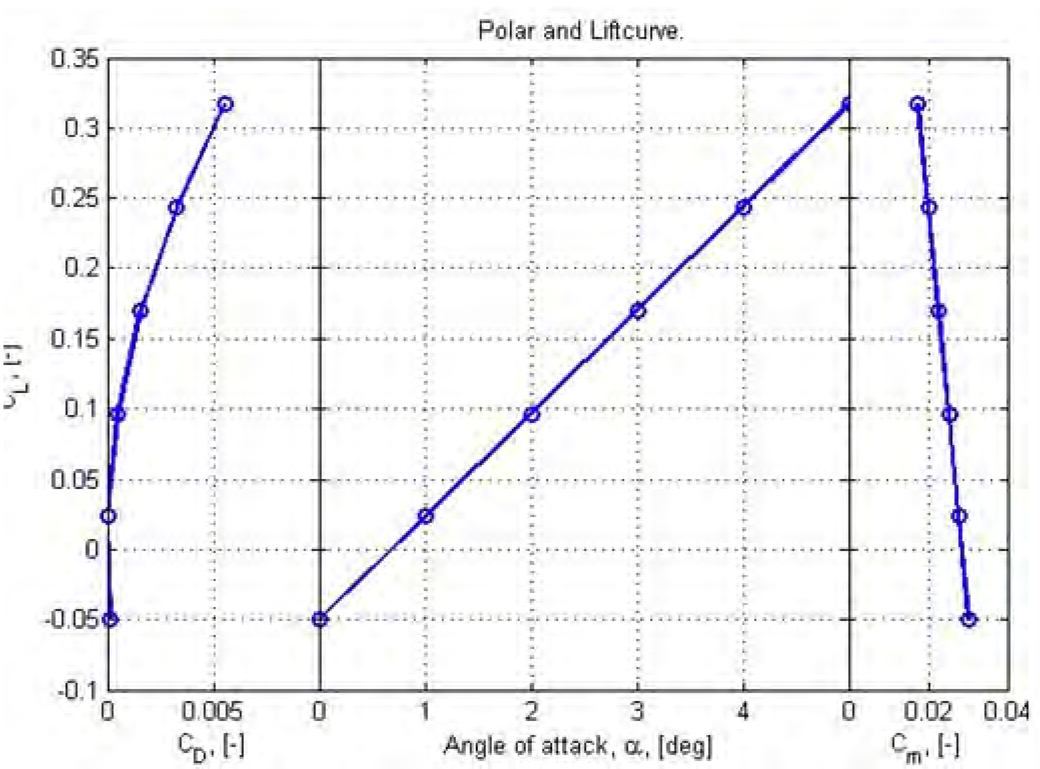
1.4
1.3
1.2
1.1
1
0.9
0.8
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


Polar and Liftcurve.
C_L, [-]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
0.005
C_D, [-]
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1
2
3
4
Angle of attack, α, [deg]
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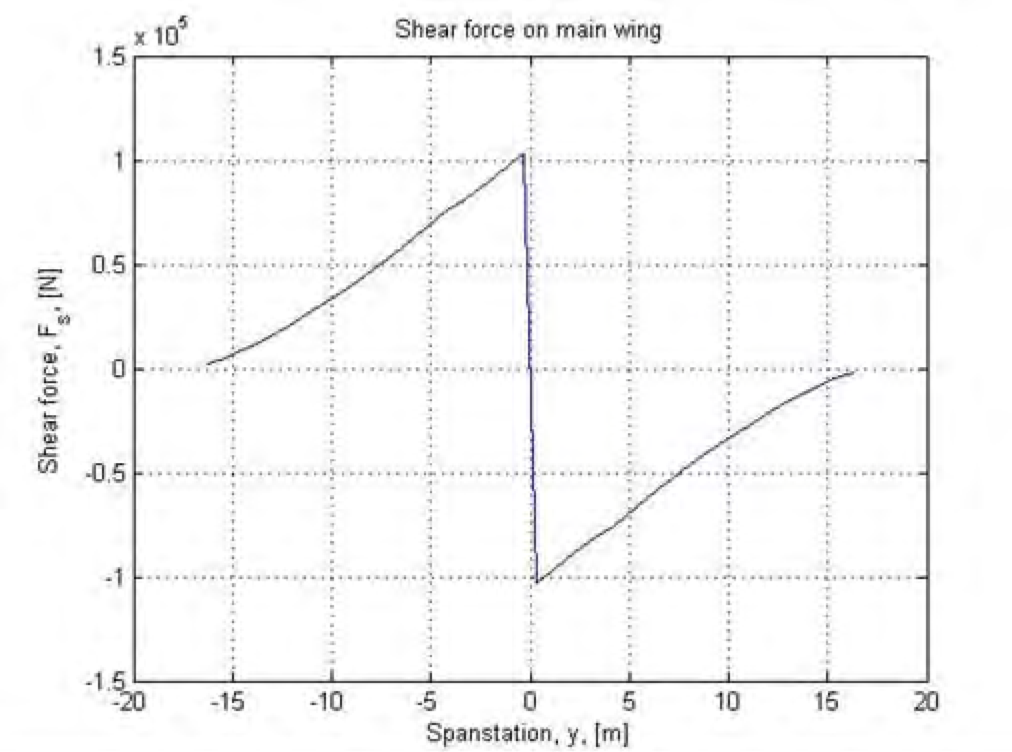
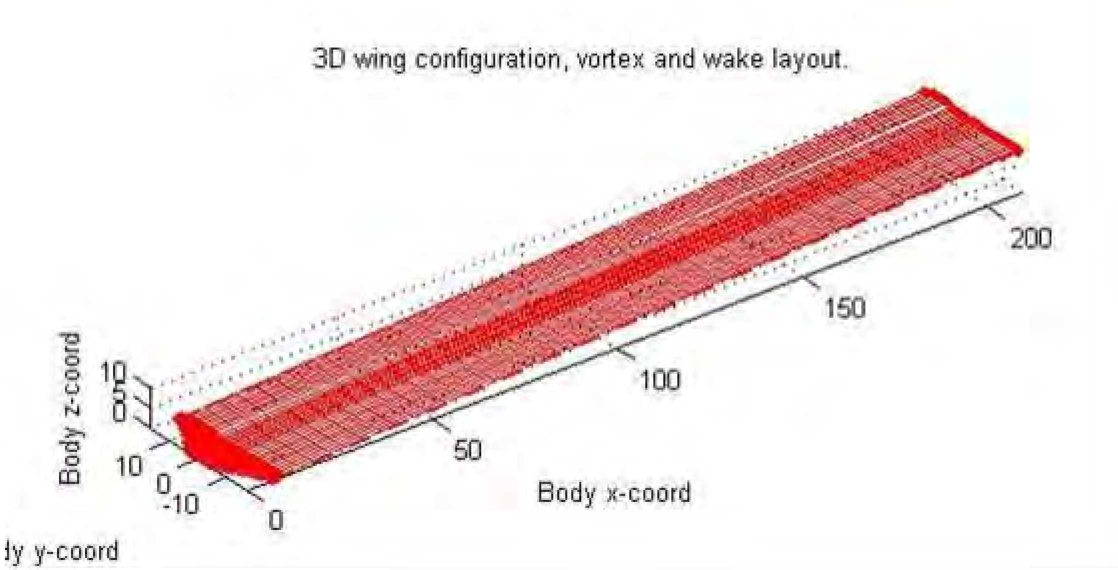
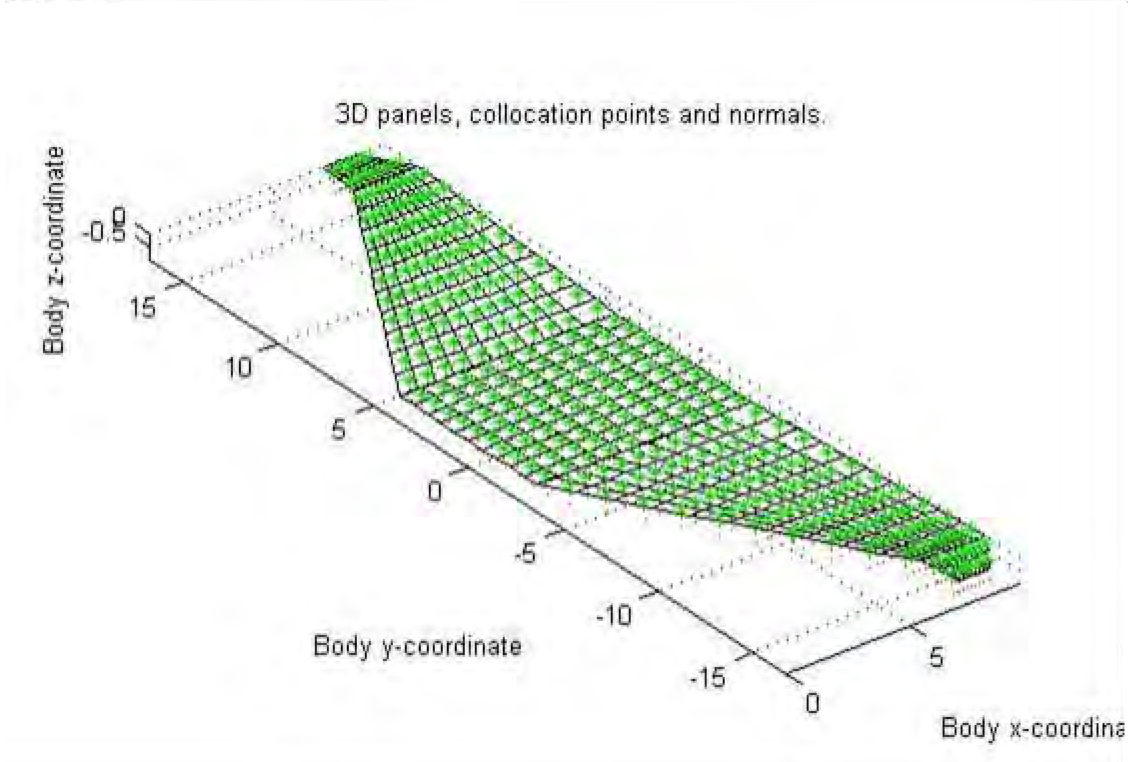
0.04
C_m, [-]


Shear force on main wing
x 10^5
1.5
1
0.5
0
-0.5
-1
-1.5
-20
-15
-10
-5
0
5
10
15
20
Shear force, F_s, [N]
Spanstation, y, [m]


3D wing configuration, vortex and wake layout.
Body z-coord
Body x-coord
dy y-coord
10
5
0
10
0
-10
0
50
100
150
200


3D panels, collocation points and normals.
Body z-coordinate
Body y-coordinate
Body x-coordina
0
-0.5
15
10
5
0
-5
-10
-15
0
5

Tornado Computation Results

JID:	888	Downwash matrix condition:	23.0977		
Reference area:	197.8597	Supersonic flow warning:	0		
Reference chord:	6.8481	Reference point pos:	3.7646	0	0
Reference span:	33.4	Center of gravity :	3.5	0	0

Net Wind Forces: (N)		Net Body Forces: (N)		Net Body Moments: (Nm)	
Drag:	1938.5528	X:	-8865.1489	Roll:	-5.9435e-010
Side:	-5.7732e-015	Y:	-5.7732e-015	Pitch:	188519.9111
Lift:	206379.0509	Z:	206197.6716	Yaw:	-7.4323e-012

CL	0.1703	CZ	0.17015	Cm	0.022716
CD	0.0015996	CX	-0.0073151	Cn	-1.8362e-019
CY	-4.7638e-021	CC	-4.7638e-021	Cl	-1.4684e-017
$CD_{trefftz}$	N/A				

STATE:

α [deg]:	3	P [rad/s]:	0		
β [deg]:	0	Q [rad/s]:	0	Rudder setting [deg]:	0 0 0
Airspeed:	100	R [rad/s]:	0		
Altitude:	0	PG Correction:	0		
Density:	1.225	Mach:	0.29386		

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